



Robust Water-Management Strategies for the California Water Plan Update 2013

Proof-of-Concept Analysis

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The research described in this report was prepared for the California Department of Water Resources and conducted in the Environment, Energy, and Economic Development Program within RAND Justice, Infrastructure, and Environment.

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Preface

About This Document

The California Department of Water Resources (DWR) is developing its 2013 update to the California Water Plan (CWP). The CWP Update 2013 will describe the current water-management conditions, evaluate future challenges facing the California water sector, and discuss potential solutions. The RAND Corporation is part of a consulting team, led by MWH Global, a global engineering consulting firm, charged with developing and implementing technical analysis that will support the CWP Update 2013. This report describes a proof-of-concept analysis supported by DWR based on the Robust Decision Making methodology, pioneered by the RAND Corporation. The proof-of-concept analysis was conducted in 2010 and 2011 to help inform the development of a plan of study for a quantitative analysis of water resource-management response packages for California's Central Valley under many scenarios reflecting future uncertainty. The intended audiences of this report include CWP stakeholders and policymakers interested in understanding the type of analysis that will be included in the CWP Update 2013.

Some content of this report and results from this research could change as a consequence of further review. Refined and revised analysis is under way and will be included in the CWP Update 2013. This report will be updated with the final CWP analysis in late 2013.

The RAND Environment, Energy, and Economic Development Program

This research reported here was conducted in the RAND Environment, Energy, and Economic Development Program, which addresses topics relating to environmental quality and regulation, water and energy resources and systems, climate, natural hazards and disasters, and economic development, both domestically and internationally. Program research is supported by government agencies, foundations, and the private sector.

This program is part of RAND Justice, Infrastructure, and Environment, a division of the RAND Corporation dedicated to improving policy and decisionmaking in a wide range of policy domains, including civil and criminal justice, infrastructure protection and homeland security, transportation and energy policy, and environmental and natural resource policy.

Questions or comments about this report should be sent to the project leader, David Groves (David_Groves@rand.org). For more information about the Environment, Energy, and Economic Development Program, see <http://www.rand.org/energy> or contact the director at eed@rand.org.

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Summary

California faces significant challenges in ensuring that its water resources successfully meet diverse needs across the state in the coming decades. Escalating needs due to population and economic growth, potentially increasing agricultural irrigation requirements, and growing desires to dedicate more water to the environment will put a strain on a system that is near or exceeds capacity. These challenges are exacerbated by potential declines in available water supply due to natural variability and climatic changes. How these long-term changes will unfold and affect California's water system is highly uncertain. It is unlikely that all future water needs can be met at all times. Addressing the future uncertainty and diversity of needs requires a planning approach that is flexible and can support deliberations over different approaches, rather than a single prescription for how to move forward.

The California Water Plan (CWP) Update 2013 analysis will use Robust Decision Making (RDM), an analytic approach to decisionmaking under uncertainty, to identify and characterize the vulnerabilities of the currently planned management approach in the Central Valley of California (the Sacramento River, San Joaquin River, and Tulare Lake hydrologic regions). The analysis will then develop and compare robust water-management response packages that could ameliorate the vulnerabilities identified. The CWP Update 2013 analysis will use a water management and planning model for the Central Valley, developed within the Water Evaluation and Planning (WEAP) modeling environment.

This report summarizes a proof-of-concept analysis developed in 2010 and 2011 and presented to the California Department of Water Resources' (DWR's) Statewide Water Analysis Network (SWAN) in May 2011.¹ The geographic scope of the proof-of-concept analysis covers a portion of the Central Valley and tributary watersheds representing the Sacramento River and San Joaquin River hydrologic regions. The CWP Update 2013 analysis will also include the Tulare Lake hydrologic region to more fully represent the Central Valley and tributary watersheds and use more-thoroughly vetted assumptions. The results shown in this report were generated to illustrate the methodology only and should not be used to draw policy conclusions.

Robust Decision Making

Traditionally, water agencies have estimated future system performance, such as reliability and cost, by using trends based on historical statistics of hydrology and best-estimate forecasts of other important factors, such as demand, regulatory conditions, and the likely increases in new

¹ SWAN serves as the voluntary technical advisory group for the California Water Plan and is made up of technical experts from local, state, and federal agencies; universities; nongovernmental organizations; and consulting firms.

supply from investments. Given increasing recognition that past climate is no longer a good predictor of future climate and of the large uncertainty in most planning factors, many agencies have increasingly incorporated handcrafted paths, called *scenarios*, into their analyses.

RDM, in contrast, provides an analytic method for developing a small number of composite scenarios that are decision relevant for a wide range of potential futures. These composite scenarios emerge directly from the analysis and provide tailored information about specific strategies and decisions that planners face. To generate these composite scenarios, RDM evaluates many thousands of different assumptions about plausible future conditions (or *futures*) and stores these results in a database. Researchers then use RDM to analyze the database to identify the key combinations of assumptions most important to determining whether or not a particular strategy meets its goals. These combinations of assumptions represent decision-relevant scenarios that can help planners to better understand the strengths and weaknesses of different management strategies and, hence, the specific conditions to which an adaptive management plan may need to respond.

Vulnerability and Response Package Analysis

Building on work performed for the CWP Update 2009, the proof-of-concept analysis presented in this report seeks to address some of the key questions that are to be answered for the CWP Update 2013, with a focus on the Central Valley:

- How would the region's current management approach perform under different plausible futures?
- What are the vulnerabilities of the current management approach?
- Which supply augmentation options could improve the performance of the current management approach?
- How would additional augmentation reduce the key vulnerabilities of the current management approach?
- What are key trade-offs among response packages?
- How does this analysis inform decisionmaking?

Researchers developed 36 future scenarios by combining three different sets of assumptions about future land use and 12 different future climate sequences derived from global climate models. The water-management model, built in the WEAP modeling environment, evaluates future management conditions for the Sacramento River and San Joaquin River hydrologic regions in terms of three key performance metrics: urban supply reliability, agricultural supply reliability, and the frequency of meeting in-stream flow requirements (IFRs). The WEAP model evaluated the current management baseline and five other response packages made up of different water-management strategies. The proof-of-concept analysis considers the notional costs of these strategies in order to support a comparison and trade-off analysis. Table S.1 summarizes the key elements of the proof-of-concept analysis.

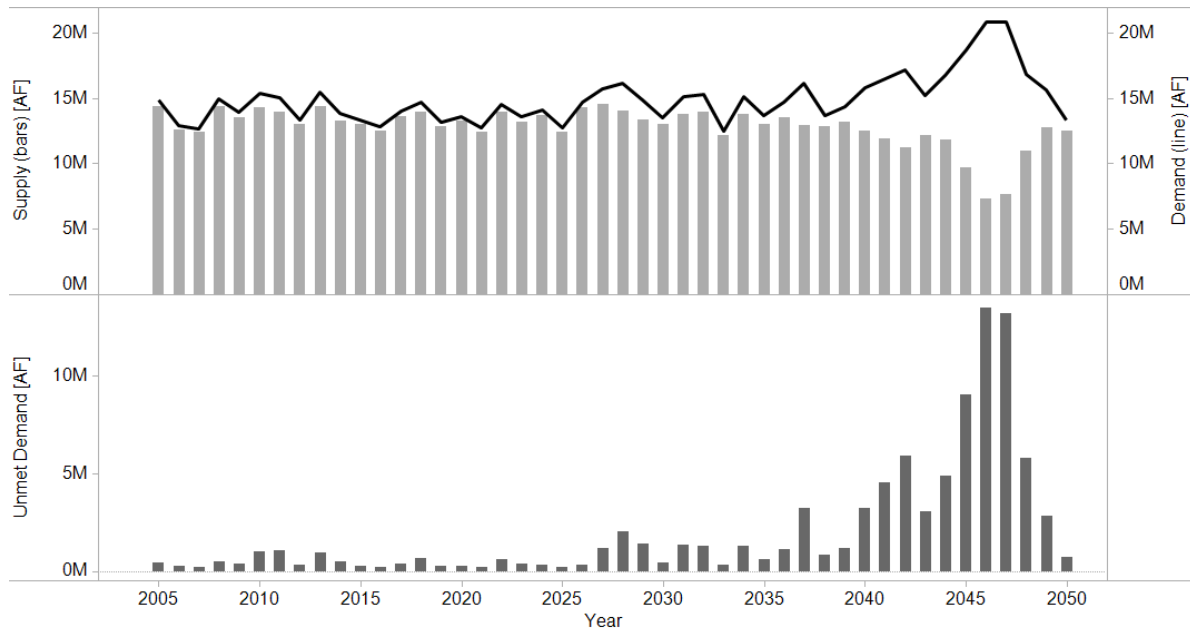
Table S.1. Summary of Uncertainties, Policy Levers, Relationships, and Metrics Identified in the Study

Uncertainties or Scenario Factors (X)	Management Strategies and Response Packages (L)
Demographic and land-use scenarios, which describe changes in <ul style="list-style-type: none"> • population • household factors • employment factors • climate sequences, which describe changes in temperature and precipitation 	Current management baseline Additional management strategies: <ul style="list-style-type: none"> • agricultural water-use efficiency • urban water-use efficiency • conjunctive management and groundwater storage • recycled municipal water
Relationships or Systems Model (R)	Performance Metrics (M)
WEAP Central Valley Model (Sacramento River and San Joaquin River hydrologic regions)	Urban supply reliability Agricultural supply reliability IFRs Notional costs

How Would the Region's Current Management Baseline Perform Under Different Plausible Futures?

We began the proof-of-concept analysis by evaluating the current management baseline across the 36 different future scenarios. In a SWAN workshop held in 2011, we showed a wide range of model outputs corresponding to individual simulations of the WEAP Central Valley Model. Figure S.1 shows an example of annual supply, demand, and unmet demand in the agricultural sector for one simulation. In this simulation, supply is adequate to meet nearly all demand until about the year 2027. At that point, rising demand and declining supply lead to significant shortages and unmet demand.

Figure S.1. Annual Supply, Demand, and Unmet Demand for the Agricultural Sector in the Study Region for One Simulation



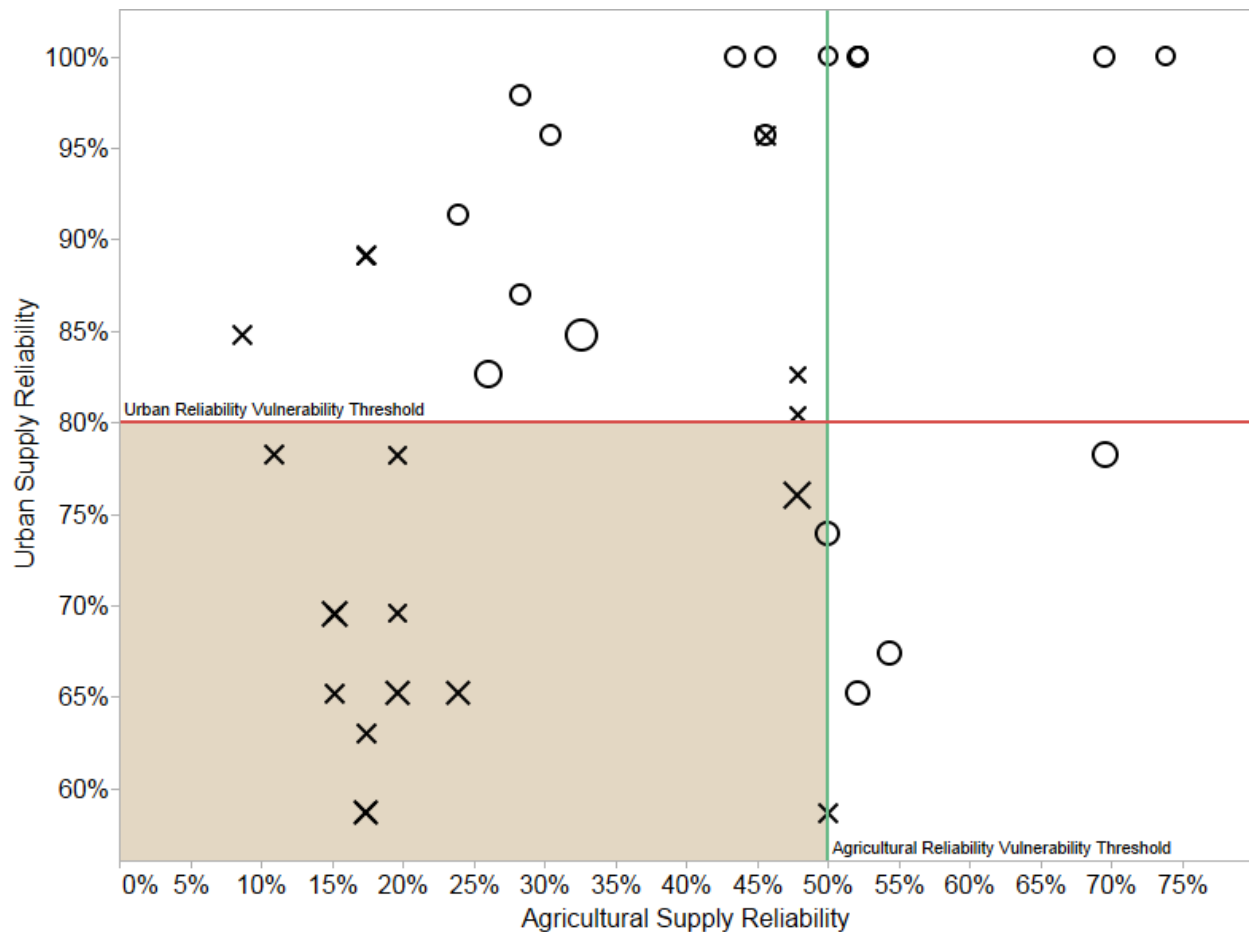
NOTE: In the upper part of the figure, the black line indicates demand and vertical bars indicate annual supply.
AF = acre-foot.

What Are the Vulnerabilities of the Current Management Baseline?

We next determined which of the simulations meet the region's goals in terms of urban and agricultural supply reliability and IFRs. Using definitions of acceptable performance set by the research team, we calculated that the current management baseline would be vulnerable in 15 of the 39 scenarios (38 percent).

Figure S.2 shows the results for urban supply reliability (vertical axis), agricultural supply reliability (horizontal axis), and percentage of years in which IFRs are not all met (size of symbols). The symbol shapes indicate whether the current management strategy is vulnerable (i.e., does not meet the thresholds for acceptable performance for two of the three metrics). All points that are to the left of the agricultural supply reliability threshold and below the urban supply reliability threshold (i.e., the shaded area) are vulnerable. In addition to those within the shaded area, some points above the shaded region in the graph are vulnerable because of poor performance on the IFR metric.

Figure S.2. Vulnerable Urban and Agricultural Supply Outcomes Across Scenarios Under the Current Management Baseline

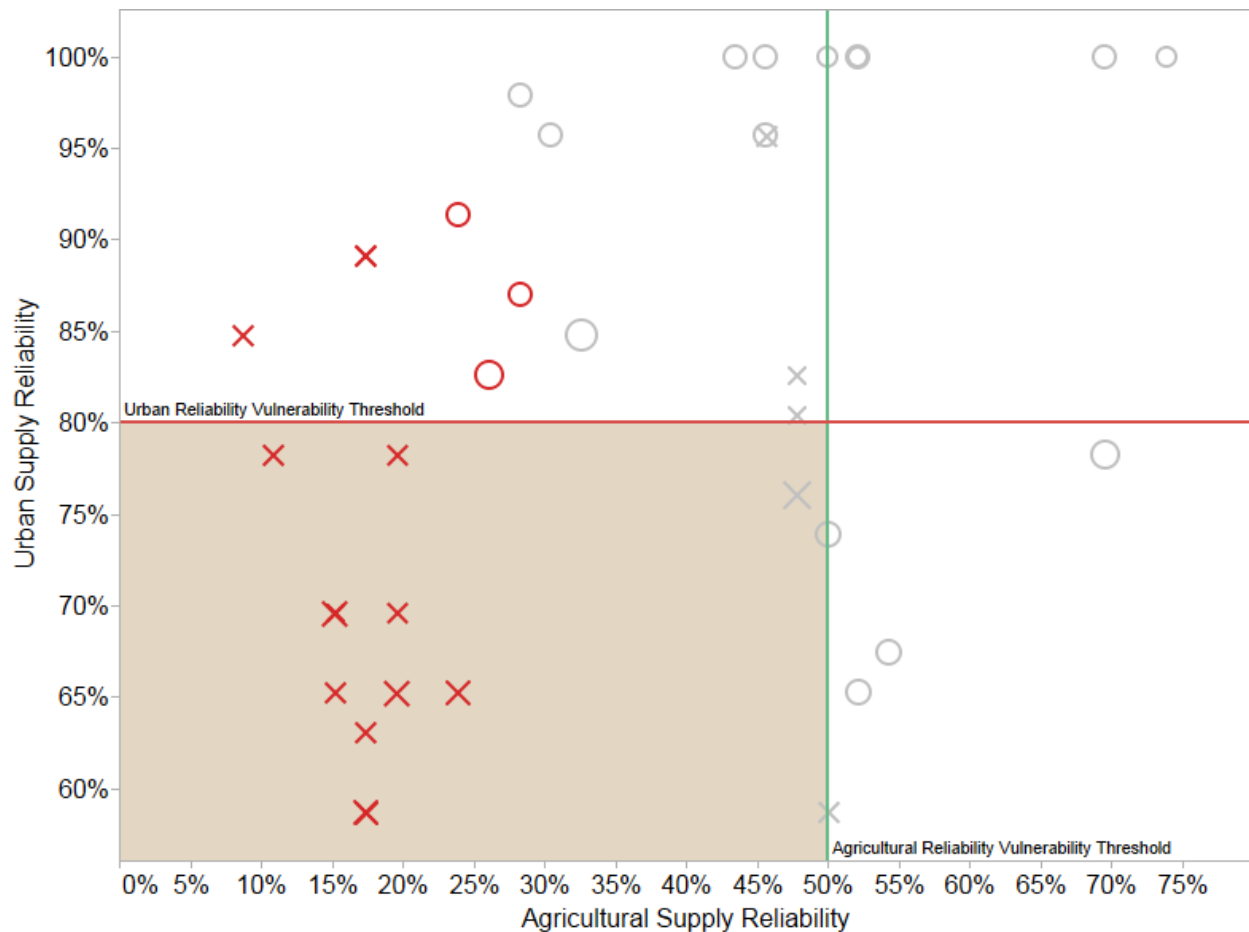


NOTE: Each point represents one future under current management conditions. The Xs represent futures in which policy objectives are not met; circles represent futures in which policy objectives are met. The size of each symbol represents the number of IFRs missed, ranging between 4.8 percent and 15.6 percent. Smaller symbols represent higher percentages of unmet requirements.

We next defined a composite *decision-relevant* scenario—those conditions that lead the current management strategy to perform poorly—using statistical scenario discovery techniques. This composite scenario is defined solely by the projected temperature trend and average annual precipitation, and we call this composite scenario the Hot and Dry composite scenario. This composite scenario accounts for 75 percent of the vulnerable futures, and 100 percent of the futures making up this scenario are vulnerable.

Figure S.3 shows the definition of the Hot and Dry composite scenario in relationship to the three performance metrics. The red symbols are those results that are described by the Hot and Dry composite scenario. One can see that the Hot and Dry composite scenario encompasses the majority of vulnerable cases but not most nonvulnerable cases.

Figure S.3. Vulnerable and Nonvulnerable Urban and Agricultural Supply Outcomes Described by the Hot and Dry Composite Scenario Across Futures Under the Current Management Baseline



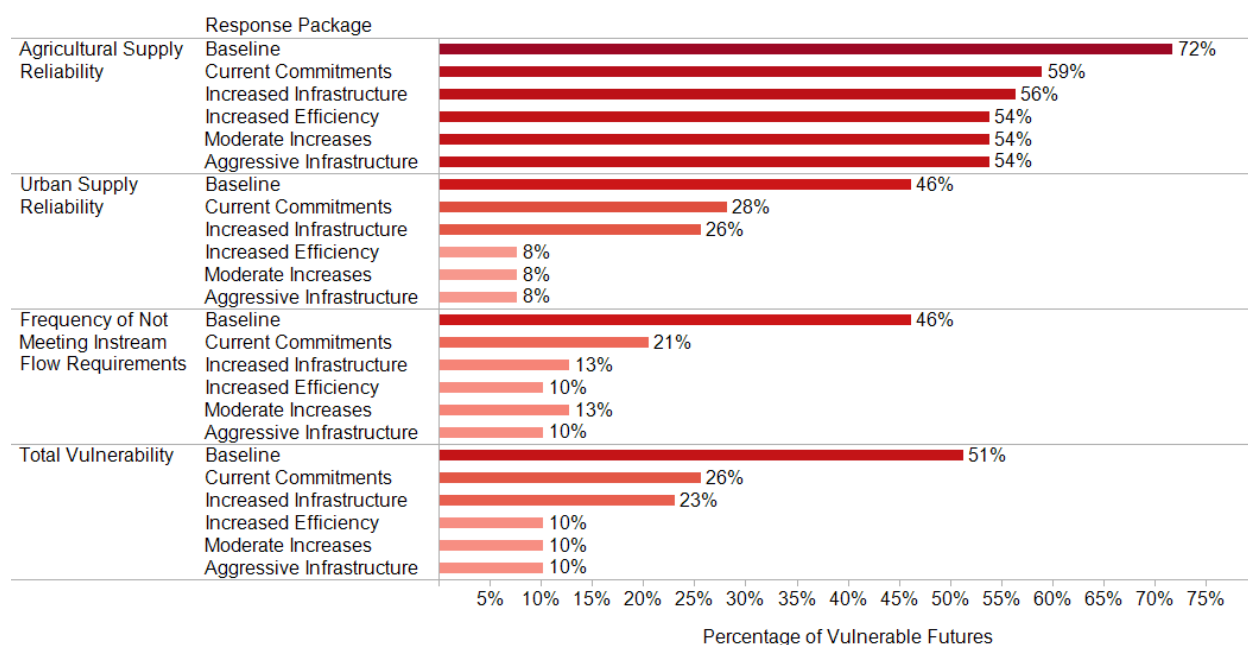
NOTE: Each point represents one future for the current management baseline. The Xs represent futures in which policy objectives are not met, and circles represent futures in which policy objectives are met. The size of each symbol represents the number of IFRs missed, ranging between 4.8 percent and 15.6 percent. Smaller symbols represent higher percentages of unmet requirements. Red symbols represent outcomes that are described by the Hot and Dry composite scenario; gray symbols represent outcomes that are not.

How Would Additional Management Strategies Reduce Vulnerabilities of the Current Management Baseline?

We next evaluated how the implementation of five different response packages would improve outcomes and reduce vulnerabilities (see Chapter Three). Figure S.4 summarizes the effect that each of the response packages has on the three performance metrics and a total reliability metric. For agricultural supply reliability, the percentage of vulnerable futures declines from 72 percent to around 55 percent for three of the five response packages—those in which agricultural efficiency improves to the greatest extent. Urban supply reliability also improves the most for the three response packages in which agricultural efficiency improves the most—declining to less than 10 percent of the futures examined. All response packages have positive

effects on the metric measuring frequency of not meeting IFRs. Across all response packages, the best outcomes are achieved for the Increased Efficiency, Moderate Increases, and Aggressive Infrastructure response packages—reducing total vulnerability from 51 percent to about 10 percent.

Figure S.4. Percentage of Vulnerable Futures for the Current Management Baseline and Five Augmentation Strategies, by the Four Reliability Metrics



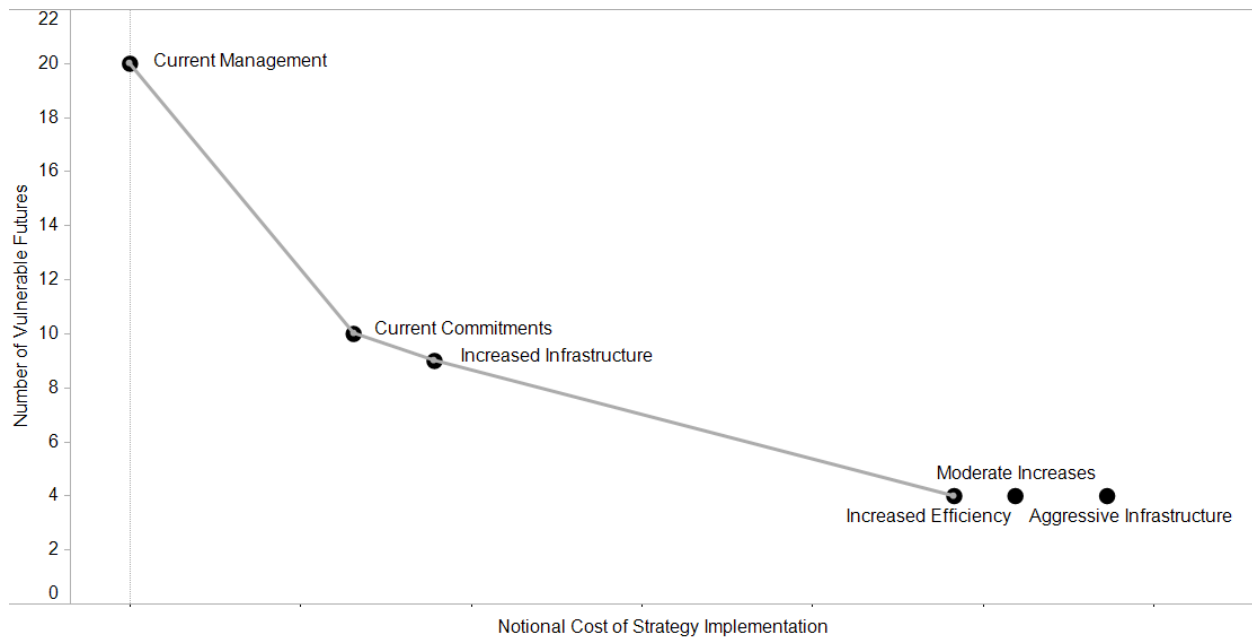
NOTE: Darker red bars indicate higher percentages of vulnerable futures.

What Are Key Trade-Offs Among Response Packages?

If level of effort and other effects of the augmentation strategies not captured by this analysis were not a consideration, the Increased Efficiency, Moderate Increases, and Aggressive Infrastructure response packages would clearly be equally preferred options. When costs of the management strategies are factored in, a trade-off emerges.

Figure S.5 plots each response package by the percentage of futures that are vulnerable for the metrics for total vulnerability (vertical axis) and notional cost of strategy implementation (horizontal axis). In general, the more-effective response packages cost more. However, additional efforts beyond the Increased Efficiency response package do not further reduce vulnerabilities. Thus, Increased Efficiency is always preferable to Moderate Increases or Aggressive Infrastructure. The line on the graph traces out a simple trade-off curve that one could consider when choosing among strategies. Note that a more involved RDM analysis would consider the cost uncertainty along with the other uncertainties when defining vulnerabilities.

Figure S.5. Trade-Off Curve of Notional Cost of Strategy Implementation and Number of Vulnerable Futures



Discussion

This analysis demonstrates how RDM might be applied to the CWP Update 2013 analysis of vulnerabilities and response packages. It shows how the WEAP Central Valley Model could be used to generate different scenarios of future conditions and how these results can be used to define those conditions that would lead to poor performance in the current management baseline. Next, the report shows how the implementation of response packages could reduce vulnerabilities and lead to a more resilient system. Then it shows one example of how the trade-off between reductions in vulnerabilities and cost for the different response packages can be used to inform long-term planning for the Central Valley.

Because of its focus on methodology, the proof-of-concept analysis was not designed to provide policy recommendations, nor does it demonstrate all aspects of RDM. The analysis under way for the CWP Update 2013 will address some but not all of these issues. Specifically, it will evaluate a larger set of scenarios to span a wider range of plausible future conditions, including climate. The WEAP model will report on a larger set of performance metrics, and the vulnerability analysis will define vulnerable conditions for each of these performance metrics. The final trade-off analysis will compare outcomes not just between reductions in total vulnerability and cost but also between reductions in vulnerability for the different performance metrics. Lastly, the final trade-off analysis will be based on improved estimates of implementation costs.

Acknowledgments

We would like to thank Rich Juricich, Mohammad Rayej, and Kamyar Guivetchi of the California Department of Water Resources for their guidance and support of this work. We benefited from the discussions and thoughtful comments received during several workshops with members of the California Statewide Water Analysis Network. Brian Joyce of the Stockholm Environment Institute and Andy Draper of MWH developed and refined the water-management model used in this study. We would also like to thank Casey Brown of the University of Massachusetts and Sarah A. Nowak of RAND for their helpful reviews. Finally, we would like to thank Keith Crane, director of the RAND Environment, Energy, and Economic Development Program, for his guidance throughout the effort.

Abbreviations

AF	acre-foot
CALFED	California Bay-Delta Program
CART	Classification and Regression Tree
CMIP3	Coupled Model Intercomparison Project Phase 3
CNRM-CM3	Centre National de Recherches Météorologiques third coupled global climate model
CWP	California Water Plan
DWR	California Department of Water Resources
GCM	general circulation model
GFDL-CM21	Geophysical Fluid Dynamics Laboratory Coupled Climate Model 2.1
GHG	greenhouse gas
IFR	in-stream flow requirement
LLNL	Lawrence Livermore National Laboratory
MAF	million acre-feet
Miroc32med	University of Tokyo Center for Climate System Research, National Institute for Environmental Studies, and Frontier Research Center for Global Change (Japan) MIROC3.2 medium-resolution global climate model
MPI-ECHAM5	Max Planck Institute ECHAM5 general circulation model
NCAR-CCSM3	National Center for Atmospheric Research Community Climate System Model, version 3.0
NCAR-PCM1	National Center for Atmospheric Research Parallel Climate Model Effort, version 1
PRIM	Patient Rule Induction Method
RDM	Robust Decision Making
SCU	Santa Clara University
SEI	Stockholm Environment Institute
SWAN	Statewide Water Analysis Network
WCRP	World Climate Research Programme
WEAP	Water Evaluation And Planning
WEAP Central Valley	a water management and planning model for the Central Valley developed within the Water Evaluation And Planning modeling environment

Chapter One. Introduction

California faces significant challenges in ensuring that its water resources successfully meet diverse needs across the state in the coming decades. Escalating needs due to population and economic growth, potentially increasing agricultural irrigation requirements, and growing desires to dedicate more water to the environment will put a strain on a system that is near or exceeds capacity. These challenges are exacerbated by potential declines in available water supply due to natural variability and climatic changes (California Department of Water Resources [DWR], 2009).

How these long-term changes will unfold and affect California's water system is highly uncertain. It is unlikely that all future water needs can be met at all times. Addressing the future uncertainty and diversity of needs requires a planning approach that is flexible and can support deliberations for different approaches, rather than a single prescription for how to move forward.

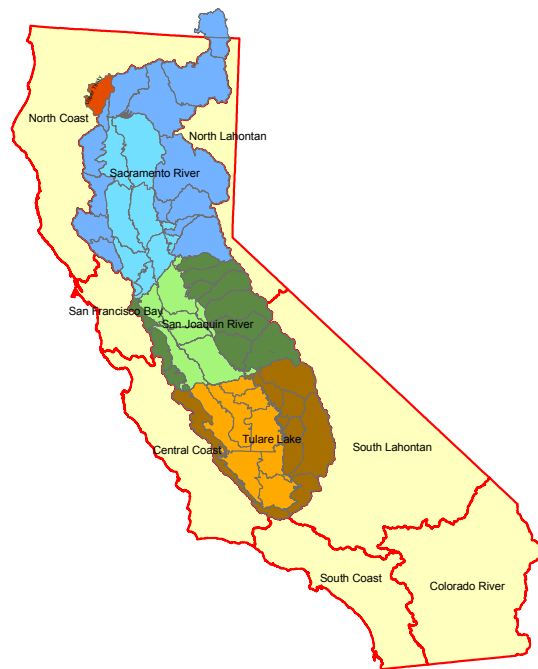
The California Water Plan

The California Water Plan (CWP) Update 2013 will build on the statewide scenario planning begun in previous efforts and include additional technical analysis of the effects of different resource-management strategies and response packages under different assumptions about uncertain future conditions. Although the CWP Update 2013 will still evaluate statewide water demand and potential resources, the analysis of response packages under uncertainty will focus only on the Central Valley watershed, including the Sacramento River, San Joaquin River, and Tulare Lake hydrologic regions (Figure 1.1).² The Central Valley is the source region for the vast majority of the state's annual precipitation. Its two major river systems drain runoff through the San Francisco Bay Delta—both a critically important natural ecosystem and the central hub of the complex California water-management system that delivers water to the southern portion of the valley and to Southern California.

The CWP Update 2013 analysis will use a water management and planning model for the Central Valley developed within the Water Evaluation and Planning (WEAP) modeling environment (WEAP Central Valley) (Joyce et al., 2010). WEAP Central Valley simulates how the water-management system could evolve over time in response to future scenarios and resource-management strategies. It computes a wide range of outputs, such as urban and agricultural reliability, in-stream flows, and groundwater levels, that can be used to assess how well a response package, made up of specific resource-management strategies, would perform in the future.

² A small portion of the North Coast hydrologic region is included in the model domain because of conveyance of surplus flows from the Trinity River.

Figure 1.1. Map of California Indicating the Central Valley Watershed



SOURCE: DWR.

NOTE: Red area indicates the connected portion of the North Coast hydrologic region. The blue, green, and orange/brown areas correspond to the Sacramento River, San Joaquin River, and Tulare Lake hydrologic regions, respectively. The lighter shaded areas indicate planning areas in the valley floor. The darker shaded areas indicate mountainous planning areas. A planning area is a subdivision of a hydrologic region.

The CWP Update 2013 analysis will use Robust Decision Making (RDM) to identify and characterize the vulnerabilities of the currently planned management approach and then to compare and develop robust water-management response packages that can ameliorate the vulnerabilities identified (Lempert and Collins, 2007; Lempert, Popper, and Bankes, 2003; Groves and Lempert, 2007). RDM is an appropriate methodology to apply to the CWP because it provides a systematic, analytic approach for evaluating different water-management responses under uncertainty. It is designed to facilitate stakeholder interaction and consensus building around near-term actions, which will prove resilient across a broad range of plausible but unknowable future conditions.

This report summarizes a proof-of-concept analysis developed during 2010 and presented to DWR's Statewide Water Analysis Network (SWAN) in May 2011.³ The geographic scope of the proof-of-concept analysis covers a portion of the Central Valley and tributary watersheds representing the Sacramento and San Joaquin River hydrologic regions. The CWP Update 2013

³ SWAN serves as the voluntary technical advisory group for the CWP and is made up of technical experts from local, state, and federal agencies; universities; nongovernmental organizations; and consulting firms.

analysis will also include the Tulare Lake hydrologic region to more fully represent the Central Valley and tributary watersheds and use more—thoroughly vetted assumptions. The results shown in this report were generated to illustrate the methodology only and should not be used to draw policy conclusions.

How This Document Is Organized

This document is organized into six chapters. Chapter Two reviews the RDM methodology applied in the report. Chapter Three describes the scope of the proof-of-concept analysis and details the data and assumptions used. Chapter Four presents the results for the vulnerability assessment of the current management baseline. Chapter Five presents an analysis of additional management strategies. In Chapter Six, we discuss our conclusions and some proposed extensions.

Chapter Two. An Overview of Robust Decision Making

Traditionally, water agencies have estimated future system performance, such as reliability and cost, by using trends based on historical statistics of hydrology and best-estimate forecasts of other important factors, such as demand, regulatory conditions, and the likely increases in new supply from investments. Given increasing recognition that the past is no longer a good predictor of future climate and of the large uncertainty in most planning factors, many agencies have increasingly incorporated handcrafted paths, called *scenarios*, into their analyses.

Scenario analyses typically consider only a small number of handcrafted paths for the future. But managers of complex water systems find themselves facing a large number of potential future scenarios because of the diversity and wide range of possible futures in terms of hydrologic supply and demand, potential regulatory changes, and other challenges. But this wide range and diversity of scenarios make it difficult to draw conclusions employing traditional system reliability analysis. Moreover, managers find it very difficult, if not impossible, to assign probabilities to these scenarios in any meaningful way (Lempert and Popper, 2005) because the uncertainty associated with the factors that differentiate scenarios is poorly understood or contentious. As a result, planning processes typically rely on ad hoc processes to reduce the number of scenarios to a manageable level to evaluate policies.

RDM, in contrast, provides an analytic method for developing a small number of composite scenarios that are decision relevant for a wide range of potential futures (Groves and Lempert, 2007; Lempert, Popper, and Bankes, 2003). These composite scenarios emerge directly from the analysis and provide tailored information about specific strategies and decisions that planners face. To generate these composite scenarios, RDM evaluates many thousands of different assumptions about plausible future conditions (or *futures*) and stores these results in a database. Using RDM, researchers then analyze the database to identify the key combinations of assumptions most important to determining whether or not a particular strategy meets its goals. These combinations of assumptions represent decision-relevant scenarios that can help planners better understand the strengths and weaknesses of different management strategies and, hence, the specific conditions to which an adaptive management plan may need to respond. RDM has been applied with increasing frequency to water-management applications (Groves, Fischbach, et al., unpublished; Groves, Lempert, Knopman, and Berry, 2008; Dessai and Hulme, 2007; Lempert, Popper, and Bankes, 2003; Means et al., 2010; Schwarz et al., 2011).⁴

⁴ Current and recently completed RAND RDM applications include work with the U.S. Bureau of Reclamation (Groves, Fischbach, et al., unpublished), El Dorado Irrigation District (Groves, Bloom, et al., forthcoming), Colorado Springs Utilities, New York City Department of Environmental Protection, the U.S. Environmental Protection Agency, and the World Bank (Lempert, Kalra, et al., forthcoming).

RDM offers a novel approach to understanding the vulnerabilities of proposed strategies and identifying factors under the planners' and resource managers' control that could make a strategy more robust against a wide range of possible future conditions. RDM is an iterative, analytic decision support methodology—sophisticated statistical and software tools embedded in a process of participatory stakeholder engagement. In the context of water management, the application of RDM facilitates the evaluation of management strategies under a wide range of potential futures—conditions reflecting uncertainty in future climate, economic, regulatory, and other areas.

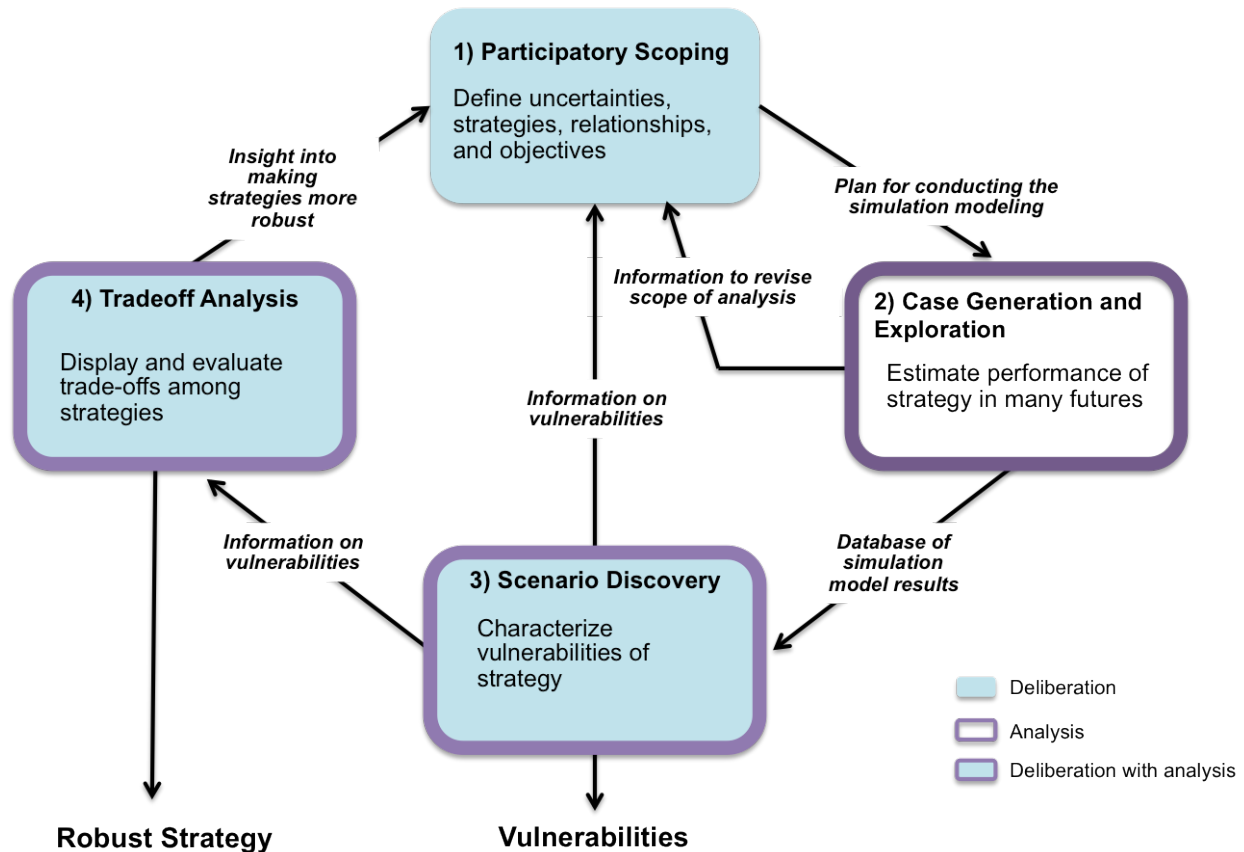
RDM helps water managers iteratively identify and evaluate *robust* strategies—those that perform well in terms of management objectives over a wide range of plausible futures but may perform less well under an assumption that one future is most likely to occur. Trading off optimality for adequacy across many possible conditions is referred to as *satisficing* (Simon, 1956). Often, the robust strategies identified by RDM are adaptive and thus designed to evolve over time in response to new information. RDM also can be used to facilitate group decisionmaking in contentious situations in which parties to the decision have strong disagreements about assumptions and values (Groves and Lempert, 2007; Lempert and Popper, 2005).

RDM helps resource managers develop adaptive strategies by iteratively evaluating the performance of leading options against a wide array of plausible futures, systematically identifying the key vulnerabilities of those strategies using statistical “scenario-discovery” algorithms (Bryant and Lempert, 2010; Groves and Lempert, 2007) and using this information to suggest responses to the vulnerabilities (Lempert and Collins, 2007; Lempert, Popper, and Banks, 2003; Means et al., 2010). Successive iterations develop and refine strategies that are increasingly robust. Final decisions among strategies are made by considering a few robust choices and weighing their remaining vulnerabilities.

Iterative Process of Robust Decision Making

RDM follows an interactive series of steps consistent with the “deliberation-with-analysis” decision support process described by the National Research Council (National Research Council Panel on Strategies and Methods for Climate-Related Decision Support, 2009) (Figure 2.1). Deliberation with analysis begins with the participants in a decision working together to define the policy questions and develop the scope of the analysis to be performed. Subsequent steps involve expert data collection, modeling, and analysis, along with deliberations based on this information in which choices and objectives are revisited.

Figure 2.1. Iterative Steps of a Robust Decision Making Analysis



The RDM process begins at the top of Figure 2.1 with a participatory scoping activity in which stakeholders and decisionmakers define their objectives and metrics, strategies that could be used to meet these objectives, the uncertainties that could affect the success of these strategies, and the relationships that govern how strategies would perform with respect to the metrics (step 1). This scoping activity often uses a framework called *XLRM*. In an *XLRM* framework (Lempert, Popper, and Banks, 2003), *X* stands for the uncertain factors that are used to develop the uncertain scenarios; *L* stands for management strategies (or *levers*) in response to the various scenarios; *R* indicates the relationships among these elements that are reflected in the planning models; and *M* is the performance metrics that are used to evaluate and compare response packages. *XLRM* provides the information needed to organize the simulation modeling, which captures the water system's response to an assumed set of external conditions related to, for example, climate, economics, regulatory requirements, and demand projections.

In step 2, analysts use the simulation model or models to evaluate the strategy or strategies in each of many plausible futures. This step in the analysis generates a large database of simulation model results (or *cases*). In step 3, analysts and decisionmakers use visualizations and scenario-discovery analysis to explore the data and identify the key combinations of future conditions in which one or more candidate strategies might not meet the agency's objectives.

The information on potential vulnerabilities that comes out of the RDM analysis provides the foundation for evaluating potential modifications of the candidate strategy or strategies that might reduce these vulnerabilities (step 4). Based on this trade-off analysis, decisionmakers may decide on a robust strategy, or they may decide that none of the strategies under consideration is sufficiently robust and return to the scoping exercise, this time with deeper insight into the strengths and weaknesses of the strategies initially considered.

There are also other paths through the RDM process. For instance, information in the database of model results may be used to identify the initial candidate strategy. In other situations, information about the vulnerabilities of the candidate strategy may lead directly to another scoping exercise to revisit objectives, uncertainties, or strategies.

Vulnerability Analysis

Step 3 of RDM—characterizing vulnerabilities of strategies—often employs statistical methods called *scenario discovery*. In some applications, it may be useful to refer to this step as *vulnerability analysis*. This analysis provides concise descriptions of the combinations of future conditions that would lead a strategy to fail to meet its objectives. These descriptions of conditions can usefully be considered to be decision-relevant scenarios in a decision support process because they focus decisionmakers' attention on the uncertain future conditions most important to the challenges they face and help facilitate discussions regarding the best ways to respond to those challenges (Bryant and Lempert, 2010; Groves and Lempert, 2007). These decision-relevant scenarios arise from a systematic analysis of performance under a wide range of future conditions, and they contrast with efforts by analysts to handcraft traditional scenarios based on intuition about the important factors driving performance.

Scenario discovery begins with the database of cases generated in step 2 of the RDM analysis. Users define minimally acceptable outcomes or satisficing thresholds for one or more performance metrics. These thresholds distinguish among cases in which a strategy does or does not meet the objectives.

In this proof-of-concept analysis, we used the Patient Rule Induction Method (PRIM) (Friedman and Fisher, 1999) to identify decision-relevant scenarios.⁵ Three measures of merit help guide this process:

- coverage: the fraction of all the vulnerable cases in the database that are contained within the composite scenario. (A vulnerable case is one in which the strategy does not meet its objectives.) Ideally, the scenario would contain all the vulnerable cases in the database, and coverage would be 100 percent.

⁵ Scenario discovery can similarly be used to identify composite scenarios in which a strategy performs especially well. Other algorithms, such as Classification and Regression Tree (CART) or principal component analysis, have also been used.

- density: the fraction of all the cases within the composite scenario that are vulnerable. Ideally, all the cases within the scenario would be vulnerable, and density would be 100 percent.
- interpretability: the ease with which users can understand the information conveyed by the composite scenario. The number of uncertain conditions used to define the scenario serves as a proxy for interpretability. The smaller the number of parameters, the higher the interpretability.

These three measures are generally in tension with one another. For instance, increasing density may decrease coverage and interpretability. PRIM thus generates a set of decision-relevant scenarios and allows the user to choose the one with the combination of density, coverage, and interpretability most suitable for his or her application.

Scenario discovery is most useful in situations in which some combinations of uncertain factors are significantly more important than others in determining whether or not a strategy meets its goals. In such situations, the analysis can help decisionmakers recognize those combinations of uncertainties that require their attention and those they believe that they can more safely ignore. Practically, for a decision analysis, scenario discovery can thus reduce the number of individual futures that need to be simulated to evaluate trade-offs among different decisions.

Chapter Three. Scope of the Proof-of-Concept Analysis

This chapter outlines the basic analytical steps followed in the report, describes the experimental design that formed the basis for generating a larger number of scenarios, and summarizes the key assumptions underlying this limited analysis. Chapters Four and Five present the results.

Building on work performed for the CWP Update 2009, the analysis addressed some of the key questions that are to be answered for the CWP Update 2013, with a focus on the Central Valley. These questions follow the five steps of RDM depicted in Figure 2.1 in Chapter Two:

- How would the region's current management approach perform under different plausible futures (steps 1 and 2)?
- What are the vulnerabilities of the current management approach (step 3)?
- Which supply augmentation options could improve the performance of the current management approach (step 1)?
- How would additional augmentation reduce the key vulnerabilities of the current management approach (steps 2 and 3)?
- What are key trade-offs among response packages (step 4)?
- How does this analysis inform decisionmaking (step 4)?

The proof-of-concept analysis demonstrated each of the steps of RDM but did not describe iteration that would be performed for an actual planning study. For example, the proof-of-concept analysis provided a preliminary look at performance trade-offs across a range of different metrics but did not include interaction with stakeholders and decisionmakers to weigh these trade-offs and use that information to help in the development of more-adaptive strategies. In a more complete application, this information could be used to identify medium-term (five to ten years) “signposts” that signify that a vulnerable outcome is becoming more likely, as well as other observable indicators of challenging conditions to support future adaptive actions.

The following sections describe the scope of the proof-of-concept analysis in terms of the key uncertain scenario factors, performance metrics, resource-management strategies and response packages, and relationships. An XLRM matrix (Lempert, Popper, and Bankes, 2003) summarizes these elements. It is designed to clearly distinguish among the uncertain factors (X) that are used to develop the uncertain scenarios; the water-management strategies (L) that make up the response packages; the relationships (R) among these elements that are reflected in the planning models; and the performance metrics (M) that are used to evaluate and compare response packages (Table 3.1). The details of Table 3.1 are described in the following sections.

Table 3.1. Summary of Uncertainties, Policy Levers, Relationships, and Metrics Identified in the Study

Uncertainties or Scenario Factors (X)	Management Strategies and Response Packages (L)
Demographic and land-use scenarios, which describe changes in <ul style="list-style-type: none"> • population • household factors • employment factors • climate sequences, which describe changes in temperature and precipitation 	Current management baseline Additional management strategies: <ul style="list-style-type: none"> • agricultural water-use efficiency • urban water-use efficiency • conjunctive management and groundwater storage • recycled municipal water
Relationships or System Model (R)	Performance Metrics (M)
WEAP Central Valley Model (Sacramento River and San Joaquin River hydrologic regions)	Urban supply reliability Agricultural supply reliability IFRs Notional costs

NOTE: IFR = in-stream flow requirement.

Because the work informing this report was a preliminary step for development of the CWP Update 2013, many elements will likely change for the final analysis. Specifically, uncertainties may be represented in different ways, additional management strategies may be considered, management strategies may be combined into different portfolios of actions to represent new response packages, and new performance metrics may be used. For the purposes of this report, decisions within the proof-of-concept analysis were made to demonstrate the analytic approach in a simple way that will be representative of the final analysis for the CWP Update 2013.

Relationships

Relationships refers to the interconnections among the different components of the climate and hydrologic systems, facilities, and operational rules and management strategies. The analysis uses a water-management model of the Sacramento River and San Joaquin River hydrologic regions developed in the WEAP software package (developed and maintained by the Stockholm Environment Institute; see Stockholm Environment Institute, undated).

This model, called the WEAP Central Valley Model (Joyce et al., 2010), simulates the major water supplies and demand for the upper watershed and valley floor, organized by DWR planning area.⁶ It is a deterministic model run on a monthly time step from 2005 to 2050. It calculates a wide range of geophysical factors representing the performance of the water-management system under a specific set of assumptions about future conditions and the implementation of water-management strategies.

⁶ There are 11 planning areas in the Sacramento River hydrologic region and ten in the San Joaquin River hydrologic region. The model includes the Sacramento and San Joaquin Rivers and their major tributaries, such as the Pit, Trinity, Feather, American, Mokelumne, and Stanislaus Rivers. Newer versions of the model include the Tulare Lake hydrologic region.

The WEAP Central Valley Model was developed at a spatial resolution appropriate to (1) simulate major hydrologic flows and exchanges and surface and groundwater storage; (2) represent major demographic and land-use trends; and (3) evaluate the effects of water-management responses. The model includes 86 demand nodes, which are grouped into four broad categories: agriculture, urban, managed wetlands, and IFRs. The model attempts to satisfy demands by diverting surface water and pumping groundwater. The extent to which the model is able to meet the full water requirements depends on the availability of surface water supplies and on capacity constraints on canals and groundwater pumping. These limitations on water supply availability and conveyance reflect physical, contractual, and legal constraints and regulatory guidelines that govern system operations. The WEAP Central Valley Model was calibrated and subsequently validated using the gridded, 0.125-degree daily climate data set of Maurer et al. (2002) for the period 1970 through 2005.

Uncertainties or Scenario Factors

Uncertainty or scenarios factors are exogenous drivers that fall outside the direct control of local water managers and other decisionmakers in California. The key uncertain exogenous drivers evaluated in the study are climate conditions and future demographics and land-use patterns.

Climate Conditions

Uncertain future climate conditions were represented by diverse time sequences of monthly temperature and precipitation applied to geographically disaggregated catchment areas in the water-management model. A historical sequence was designed to test the effects of drought conditions experienced in the recent past at different times in the future. Historical climate conditions were derived from a gridded historical data set for 1950 to 2010 (Maurer et al., 2002). These historical temperature and precipitation estimates include two recent, significant droughts: from 1976–1977 and from 1987–1992.

Other sequences were based on transient projections of temperature and precipitation from global climate models (Atmosphere-Ocean General Circulation Models, or GCMs). The analysis evaluated 12 sequences of global transient projections of temperature and precipitation, downscaled to a grid approximately 12 km by 12 km for the Central Valley study area. These sequences were also used in the CWP Update 2009. The sequences correspond to the 12 model/emission scenario combinations selected by the governor’s Climate Action Team (Maurer and Hidalgo, 2008).⁷

⁷ These sequences were downscaled using the bias-correction/spatial-downscaling method. Validation studies show adequate performance for monthly-based hydrologic studies (Maurer and Hidalgo, 2008).

The GCMs used were

- Centre National de Recherches Météorologiques third coupled global climate model (CNRM-CM3) (France)
- Geophysical Fluid Dynamics Laboratory climate model (GFDL-CM21) (United States)
- University of Tokyo Center for Climate System Research, National Institute for Environmental Studies, and Frontier Research Center for Global Change medium-resolution (miroc32med) global climate model (Japan)
- Max Planck Institute ECHAM5 GCM (MPI-ECHAM5) (Germany)
- National Center for Atmospheric Research Community Climate System Model, version 3.0 (NCAR-CCSM3) (United States)
- National Center for Atmospheric Research Parallel Climate Model Effort, version 1 (NCAR-PCM1) (United States).

The two emission scenarios used were the A2 and B1 scenarios (Nakicenovic et al., 2000). As summarized by the California Climate Action Team (2009, p. 17),

The A2 SRES global emissions scenario represents a heterogeneous world with respect to demographics, economic growth, resource use and energy systems, and cultural factors. There is a de-emphasis on globalization, reflected in heterogeneity of economic growth rates and rates and directions of technological change. These and other factors imply continued growth throughout the 21st century of global GHG [greenhouse-gas] emissions. By contrast, B1 is a “global sustainability” scenario. Worldwide, environmental protection and quality and human development emerge as key priorities, and there is an increase in international cooperation to address them as well as to convergence in other dimensions. Neither scenario entails explicit climate mitigation policies. The A2 and B1 global emission scenarios were selected to bracket the potential range of emissions and the availability of outputs from global climate models.

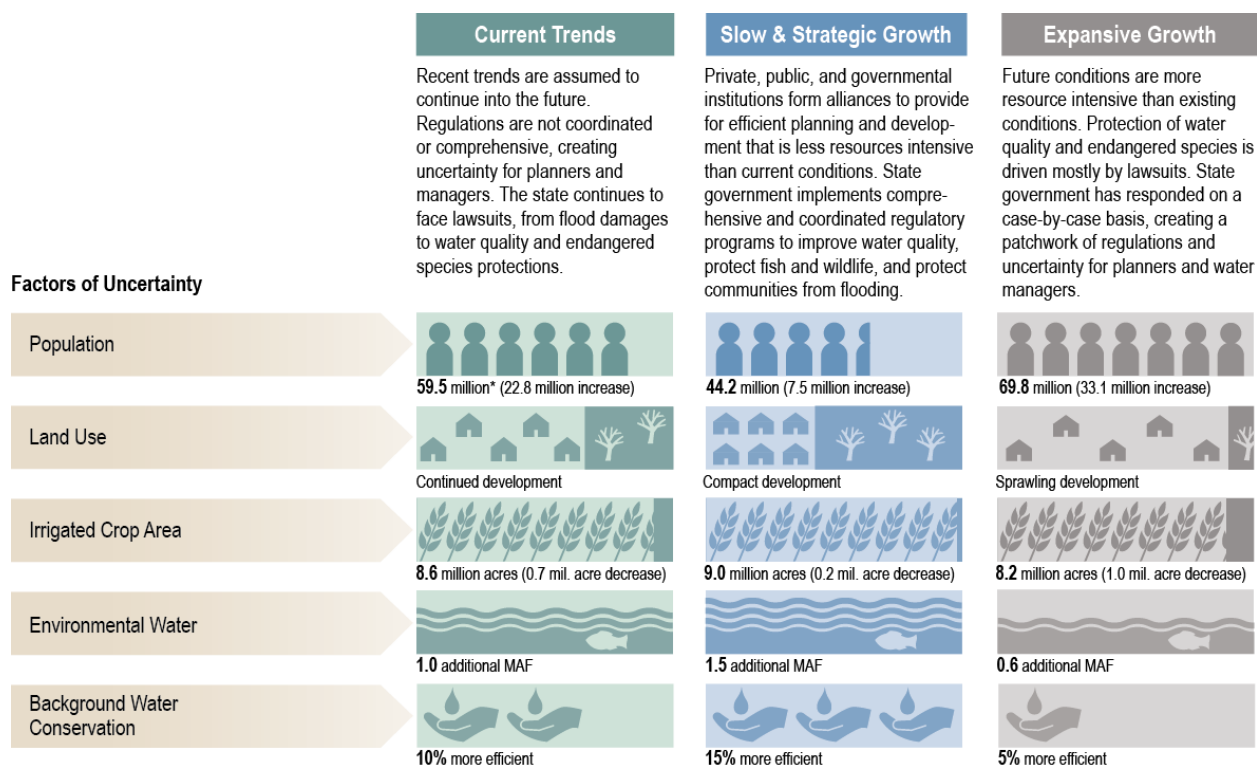
Although these 12 GCM projections expand the range of future plausible hydrologic conditions relevant to the performance of the Central Valley water-management system, these estimates may still underestimate the plausible range of future temperature and precipitation trends in the western United States. For instance, these projections do not provide a significant sample of conditions that are both hotter and wetter. These projections may also underestimate the range of future interannual variability, including the potential for multiyear droughts (Brown and Wilby, 2012; Cayan et al., 2010).

Downscaled monthly temperature and climate projections were obtained from the downscaled climate data set jointly developed by the Lawrence Livermore National Laboratory (LLNL), the U.S. Department of the Interior, the U.S. Bureau of Reclamation, and Santa Clara University (SCU) (see LLNL, 2013). These data were derived from the World Climate Research Programme’s (WCRP’s) Coupled Model Intercomparison Project Phase 3 (CMIP3) multimodel data set and include data from 112 different global climate simulations of 16 global models evaluated for three global emission scenarios. The projections are available for 1950 through 2099.

Demographic and Land-Use Scenarios

The WEAP model was evaluated using three different demographic and land-use scenarios first described in the CWP 2009 Update: Current Trends, Slow and Strategic Growth, and Expansive Growth (Figure 3.1). Each has a different pattern in population, land use, irrigated crop area, environmental requirements, and water conservation.

Figure 3.1. Demographic and Land-Use Scenarios from the California Water Plan Update 2009



SOURCE: DWR, 2009.

NOTE: MAF = million acre-feet. Asterisk indicates Department of Finance population projection.

Three key WEAP model parameters were adjusted to model each of these scenarios:

- population, households, and employees: Estimates of population, number of households, and number of employees in each planning area were set to be consistent with each scenario description for each year of the simulations (Table 3.2).
- irrigated land area: Acreages of land area irrigated, by crop and planning area, were set to be consistent with each scenario description.
- environmental IFRs: Per the CWP Update 2009 scenario descriptions, the priority of meeting environmental IFRs in the water-management model were set to differ by land-use scenario:

- Current Trends and Expansive Growth: Flow requirement priorities were set lower than indoor urban demand and set equal to outdoor urban and agricultural water demand.
- Slow and Strategic Growth: Flow requirement priorities were set equal to the priority of indoor urban demand.

Table 3.2. Assumptions for 2005 and 2050 for Three Demographic and Land-Use Scenarios

Demographic Factor	2005	2050		
		Current Trends	Slow and Strategic Growth	Expansive Growth
Population	4,874,181	10,234,497	7,435,123	11,106,170
Households	1,712,739	3,541,561	2,625,778	3,740,594
Employees	2,467,097	5,486,577	4,403,810	5,838,373

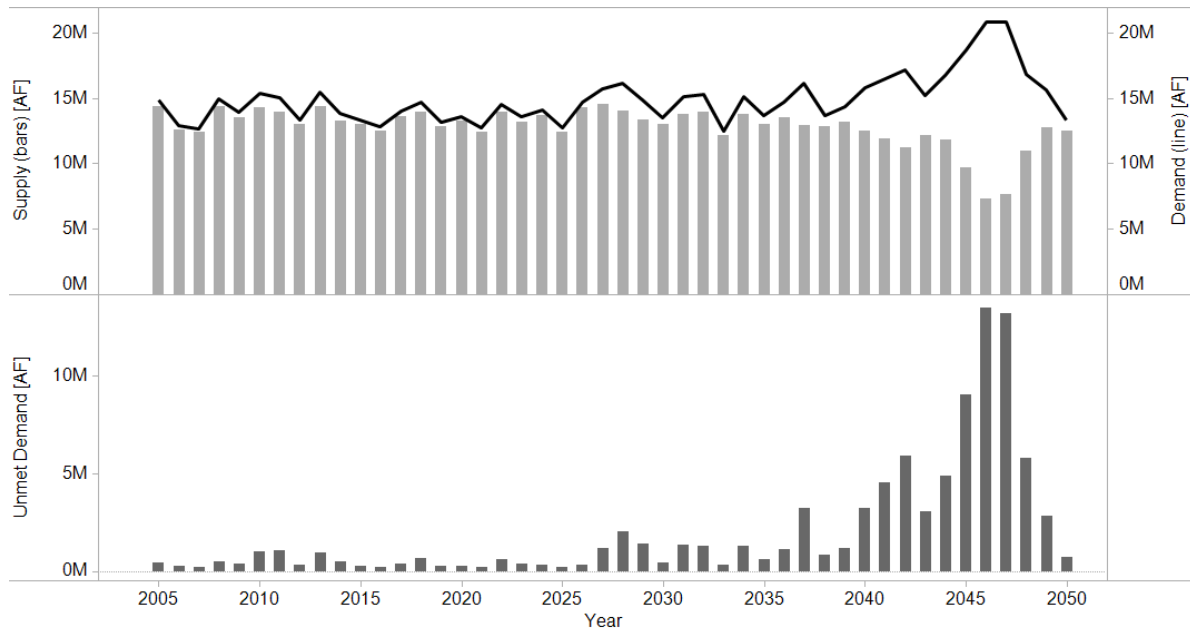
Performance Metrics

Performance metrics are used in the RDM analysis to quantify how the water-management system would perform under different future conditions and response packages. They are derived from a subset of the many available WEAP model outputs. As part of the SWAN workshops in 2011, outputs corresponding to individual simulations of the WEAP Central Valley Model were shown (Figures 3.2 and 3.3). The upper panel in Figure 3.2 shows annual projected water demand and supply for agricultural uses across both hydrologic regions for one particular case. The lower panel shows the difference, which is the projected unmet agricultural water demand. In this particular run, demand rises and supply decreases near 2045, creating shortages of water. Note that this is only one of 234 different cases of the model; results differ significantly between cases.

In Figure 3.3, the upper panel shows total projected groundwater supply across both hydrologic regions. The model constrains groundwater supply to not dip below approximately 90 MAF, the historical low. In this particular case, groundwater supply begins approaching this lower bound following 2035 and never increases significantly above it again. The lower chart shows total projected reservoir storage. Total reservoir storage reaches a low in 2046. Once again, results in other cases differ significantly.⁸

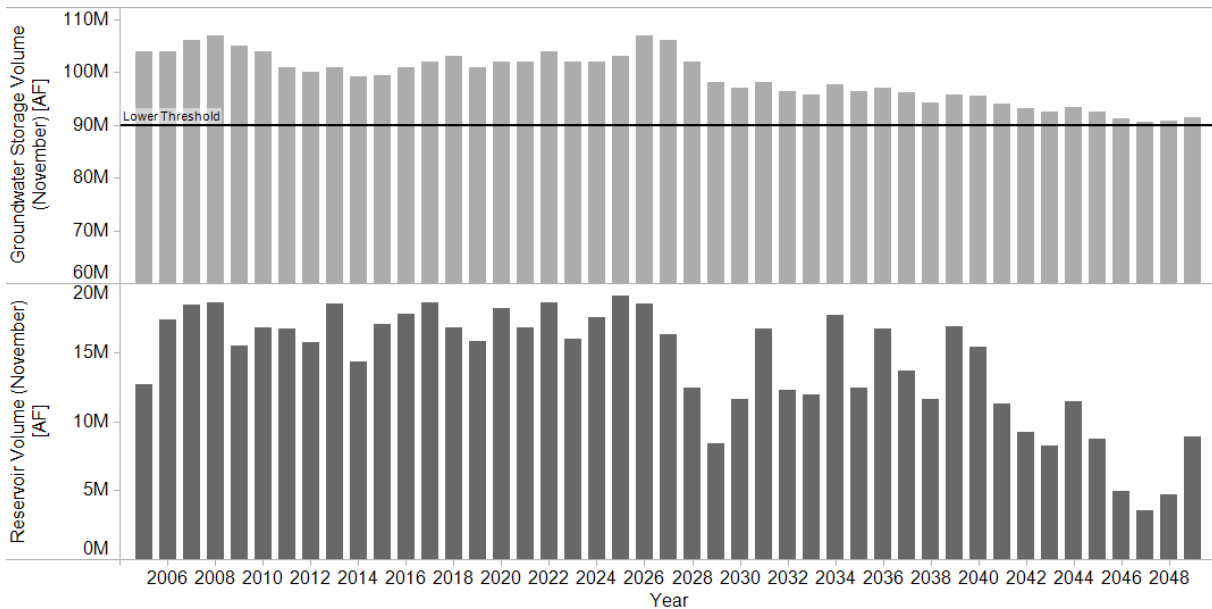
⁸ Similar graphics have been generated in an accompanying interactive workbook for a variety of other outcomes.

Figure 3.2. Annual Supply, Demand, and Unmet Demand for the Agricultural Sector in the Study Region for One Simulation



NOTE: AF = acre-foot. In the upper part of the figure, the black line indicates demand, and vertical bars indicate annual supply.

Figure 3.3. Total Groundwater and Reservoir Storage in November for One Simulation



The proof-of-concept analysis developed four performance metrics to focus on key outcomes of interest to stakeholders in consultation with DWR and other team members (Table 3.3). The first three metrics were calculated directly from the WEAP model output. To illustrate trade-offs

among the strategies, the fourth metric—notional cost of strategy implementation—was developed based on a literature review. The CWP Update 2013 will refine these estimates.

Table 3.3. Performance Metrics

Performance Metric	Definition	WEAP Output
Urban supply reliability	Percentage of years in which unmet urban demand does not exceed 1% of urban demand	Unmet urban demand
Agricultural supply reliability	Percentage of years in which unmet agricultural demand does not exceed 5% of agricultural demand	Unmet agricultural demand
Frequency of not meeting IFRs	Percentage of months in which IFRs are not met	Unmet IFRs
Notional cost of strategy implementation	Rough estimate of cost for implementing water-management strategies	Not applicable; cost estimates were developed outside the WEAP model

Management Strategies and Response Packages

The CWP defines management strategies as specific resource-management approaches to improve water-management outcomes. Response packages are combinations of strategies that could make up a comprehensive approach to addressing current and future water-management challenges. The analysis defined a small set of example management strategies and then modeled several response packages made up of different combinations of strategy implementations.

Management Strategies

Volume 2 of the CWP Update 2009 describes 27 different resource-management strategies for California, ranging from increased water-use efficiency to new surface storage facilities to watershed management. The CWP WEAP model can represent a subset of these water strategies (Table 3.4).

Table 3.4. Water-Management Strategies That Could Be Simulated by a Water-Management Model

Strategy Type	CWP Strategy
Reduce water demand	Agricultural water-use efficiency* Urban water-use efficiency*
Improve operational efficiency	Conveyance: delta Conveyance: regional and local System reoperation Water transfers Conjunctive management and groundwater storage*
Increase water supply	Desalination: brackish and seawater Precipitation enhancement Recycled municipal water* Surface storage: CALFED and state Surface storage: regional and local

NOTE: Asterisks indicate strategies evaluated in this analysis. CALFED = California Bay-Delta Program.

The proof-of-concept analysis considered an even smaller set of strategies, focusing on those that could be represented simply in the water-management model and those that were anticipated to have a significant effect on the high-level performance metrics (those listed in Table 3.3).

Agricultural Water-Use Efficiency

Agricultural water-use efficiency is the use and application of scientific processes to control agricultural water delivery and achieve a beneficial outcome (see Vol. 2, Chapter Two of the CWP Update 2009). Improvements in agricultural water-use efficiency occur primarily as a result of three activities:

- hardware: improving on-farm irrigation systems and water-supplier delivery systems
- water management: improving management of on-farm irrigation and water-supplier delivery systems
- crop water consumption: reducing nonbeneficial evapotranspiration.

The water-management model implements irrigation efficiency strategies through the adjustment of irrigation thresholds for soil moisture. These thresholds were calibrated based on current demand conditions for each crop in the local area. To approximate a decrease in demand due to efficiency, these thresholds were adjusted to achieve specified percentage decreases in demand.⁹

⁹ This calibration was completed under historical climate conditions for one representative planning area in each hydrologic region. Each planning area has different acreage for each of 21 different crops; this calibration was completed separately for each crop. Sensitivity testing was conducted to ensure that the calibrations were approximately accurate under other climate conditions. Levels of agricultural water-use efficiency were set in the model to increase gradually between 2010 and 2020.

Urban Water-Use Efficiency

Urban water-use efficiency can be achieved through a broad array of individual and local actions. California has already implemented policies to provide incentives for those actions, including the following:

- standards, such as requiring urban water agencies to reduce use by 2020
- funding mechanisms, such as requiring water agencies to implement urban best management practices to be eligible for loans and grants (see Vol. 2, Chapter Three of the CWP Update 2009).

Urban water-use efficiency was modeled separately for indoor and outdoor urban demand for this report. For indoor urban demand locations, demand rates per household, employee, and capita (for public water use) were simply scaled by a specific percentage to represent the adoption of increased water-use efficiency. Levels of urban water-use efficiency were set to increase gradually over time. Outdoor water use was calculated by WEAP, using estimates of the area of irrigated landscaping, the required water use for landscaping, and the evapotranspiration requirements of the total landscape over time. Increased efficiency was modeled using the same process as for agricultural water-use efficiency.

Conjunctive Management and Groundwater Storage

Conjunctive management is the coordinated and planned use and management of surface-water and groundwater resources to maximize the availability and reliability of water supplies in a region to meet various management objectives. Operationally, this can be implemented by storing surface water in the groundwater basin when plentiful and shifting to groundwater use during periods of surface-water supply shortages (see Vol. 2, Chapter Eight of the CWP Update 2009).

Conjunctive management is represented in the water-management model by adding additional demand nodes that represent the monthly maximum volume of water that could be injected into representative groundwater basins. These demand nodes are connected to the main stem of the Sacramento and San Joaquin Rivers and specified to divert water only after all urban, agricultural, environmental, and other water demands are met. All conjunctive groundwater-management sites were set in the model to become active in 2020.

Recycled Municipal Water

Recycled municipal water is wastewater treated for reuse for irrigation and industrial purposes (see Vol. 2, Chapter Eleven of the CWP Update 2009). Recycled water is modeled in WEAP by routing unconsumed urban water via wastewater treatment nodes back to outdoor urban and agricultural demand nodes within the same planning area. These wastewater treatment nodes were set to treat a specified percentage of water supplied from their source nodes. Levels of recycled municipal water were set in the model to increase gradually over time at a rate consistent with plausible development of reuse in each hydrologic region.

Response Packages

Combinations of management strategies were grouped together to form response packages. Each response package represents different levels of urban water-use efficiency, agricultural water-use efficiency, conjunctive management, and recycled water use. The proof-of-concept analysis generated representative response packages, drawing high-level estimates of yield and cost for each project from a range of sources, described in the following sections.

Note that, in the proof-of-concept analysis, each strategy was assumed to be completely effective in achieving the intended outcome. For example, the Current Commitments response package assumed that a 20-percent increase in urban water-use efficiency is achieved, rather than trying to explicitly estimate the effects of the various agency policies expected to be implemented to meet California's 20 × 2020 water-use efficiency regulation. The effects of the management strategies were modeled to increase linearly between 2005 and 2020, with exception of conjunctive use, which was modeled to be completely effective all at once at 2020.

Table 3.5 summarizes the current management baseline and five different response packages that reflect increasing levels of water-management strategy implementation. The following sections describe each in more detail.

Table 3.5. Summary of Current Management Baseline Strategy and Response Packages

Current Management Baseline or Response Package	Increase in Urban Water-Use Efficiency (%)	Increase in Agricultural Water-Use Efficiency (%)	Conjunctive Management and Groundwater Storage	Recycled Municipal Water (%)
Current management baseline	0	0	None	0
Current Commitments	20	0	None	10
Increased Infrastructure	20	0	Low recharge	25
Increased Efficiency	30	6	None	10
Moderate Increases	30	6	Low recharge	25
Aggressive Infrastructure	30	6	High recharge	50

Current Management Baseline

The current management baseline reflects a condition in which current water management persists through the simulation period.

Current Commitments

This response package modifies the baseline package by approximating expected increases in urban water-use efficiency (due to the 20 × 2020 regulation) and increases in recycled water use consistent with a rough survey of 2010 Urban Water Management Plans within the Central Valley.

Increased Infrastructure

This response package represents modest increases in infrastructure projects—conjunctive management and recycled municipal water. The rate of increase in recycling was based on CALFED’s *Water Use Efficiency Comprehensive Evaluation* (CALFED, 2006). Sources for potential conjunctive management sites were based on the 1999 CALFED *Conjunctive Use Site Assessment* (CALFED, 1999). That study estimated recharge rates for nine potential groundwater banking sites and mapped them to eight sites within the WEAP model. The low recharge rates represent the lower bound of potential recharge described in that report.

Increased Efficiency

This response package increases efficiency beyond 20 × 2020 and keeps other strategies the same as in Current Commitments. The 30-percent increase in urban water-use efficiency was chosen after reviewing the CWP Update 2009 (DWR, 2009), CALFED’s *Water Use Efficiency Comprehensive Evaluation* (CALFED, 2006), and the *20 × 2020 Water Conservation Plan* (DWR, 2010). The 6-percent increase in agricultural efficiency was chosen after reviewing various documents, including the CWP Update 2009, the Pacific Institute’s *Sustaining California Agriculture in an Uncertain Future* (Cooley, Christian-Smith, and Gleick, 2009), CALFED’s *Water Use Efficiency Comprehensive Evaluation* (CALFED, 2006). This 6-percent agricultural efficiency value represents an approximate average across the studies reviewed. A complete analysis should consider a wider range of values.

Moderate Increases

This response package represents the combination of increases in both previous management strategies.

Aggressive Infrastructure

This response package represents further increases in use of recycled water and in conjunctive management. The high recharge rates in conjunctive management represent the high upper bounds of recharge found in *Conjunctive Use Site Assessment* (CALFED, 1999).

Experimental Design

To generate a large number of cases that cover a wide range of possible futures, the project team developed an experimental design specifying the values for each uncertain condition to generate a large set of future cases. WEAP simulations were then run to support the analysis. The first experimental design focused on the performance of the current management baseline, and the second experimental design considered the performance of response packages, across the same range of uncertainty.

The project team developed a full-factorial experimental design for the scenario factors to test the vulnerability of the current management baseline:¹⁰

13 climate sequences \times 3 demographic or land-use scenarios = 39 sampled futures.

Combining these factors in the experimental design led to the specification of 39 sampled futures. The study evaluated each of the five adaptation strategies for the 39 sampled futures for 195 additional simulations.

This proof-of-concept analysis used a relatively small experimental design to minimize computational requirements. Other RDM studies (e.g., Groves, Knopman, et al., 2008; Bureau of Reclamation, 2012) have explored wider ranges of uncertainty by looking at thousands of futures. The analysis for the CWP Update 2013 will evaluate a wider range of scenarios and response packages.

¹⁰ A full-factorial design includes all possible combinations of a finite set of values for each factor.

Chapter Four. Results: Vulnerability of the Current Management Baseline

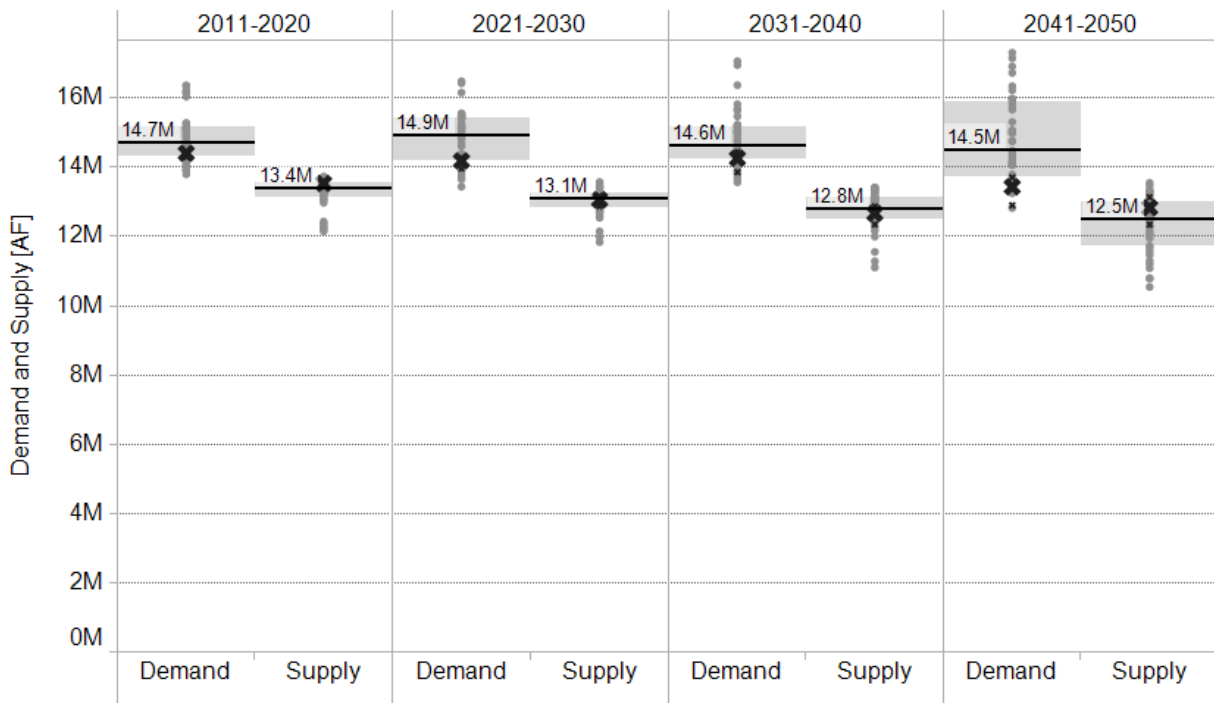
In this chapter, we describe the proof-of-concept analysis of the vulnerability of the Central Valley's current water management. These results illustrate the use of RDM in identifying and characterizing the conditions in which the current management baseline would perform poorly. In Chapter Five, we describe the results of our proof-of-concept analysis. They show how response packages for the Central Valley could reduce these vulnerabilities, and they highlight the key trade-offs that water managers would need to make among the different strategies. Results are presented as answers to the questions that the report was designed to address, as listed in Chapter Three.

How Would the Region's Current Management Baseline Perform Under Different Plausible Futures?

We first evaluate how the current management system would perform across 39 different scenarios (see Table 3.6 in Chapter Three) using the WEAP Central Valley Model. The distribution of agricultural demand and supply results (across the 39 scenarios) in Figure 4.1 shows slightly declining supply and demand and that total agricultural demand is generally larger than supply during all time periods—the median amount is about 10 percent higher in the first decade and 16 percent higher in the last decade. Most of this excess demand is concentrated in a few regions of the San Joaquin River hydrologic region. The spread across the scenarios is slightly larger for demand than it is for supply, reflecting sensitivity of demand to differences in climate that is not as apparent in the groundwater supply used to support much of the region's agricultural use.

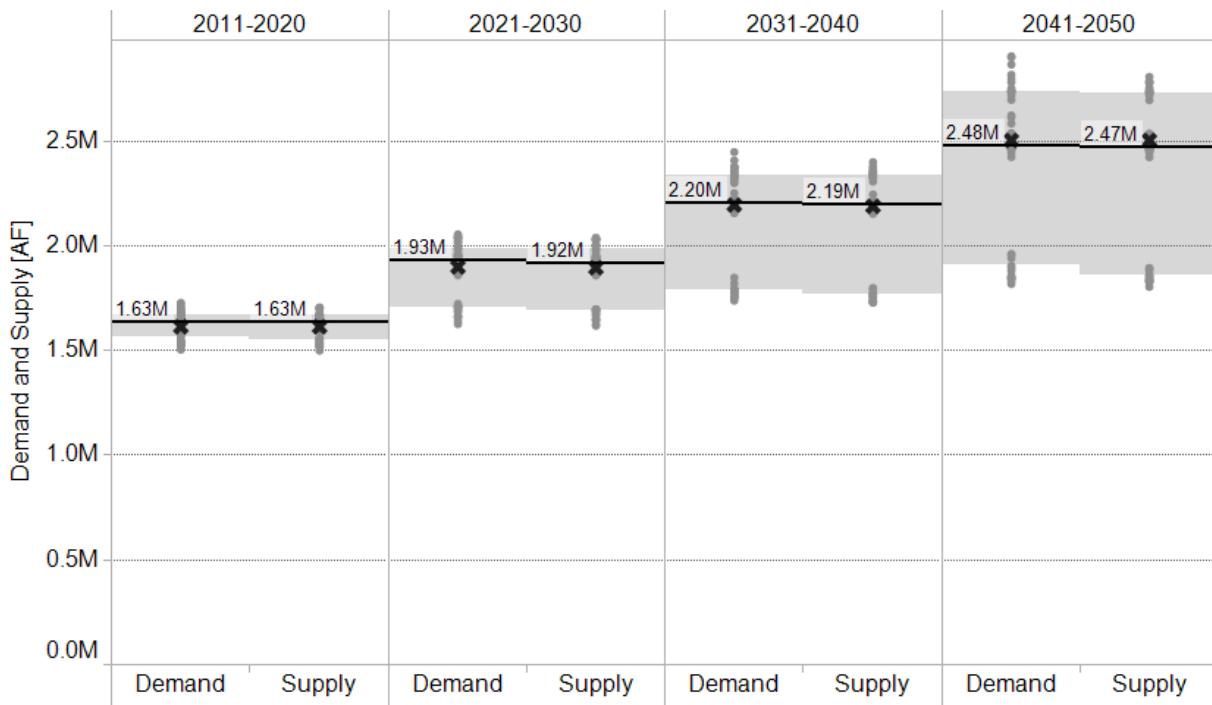
The distribution of urban demand and supply results in Figure 4.2 shows similar distributions of supply and demand for each decade and decade-over-decade increases in both. Note that agricultural demand for the Current Trends land-use/Historical climate scenario is at the low end of the range, suggesting that warmer and drier conditions reflected in the GCM scenarios are driving range of agricultural demand. For urban demand, however, the Current Trends land-use/Historical climate scenario is close to the middle of the distribution for demand, reflecting the land-use scenarios' stronger influence on urban demand.

Figure 4.1. Distribution of Central Valley Agricultural Supply and Demand, by Decade



NOTE: Gray circles indicate individual scenario results. Horizontal solid lines indicate the median results across all scenarios. Shading indicates the 25th to 75th interquartile range. Dark Xs indicate results for the Current Trends land-use/Historical climate scenario.

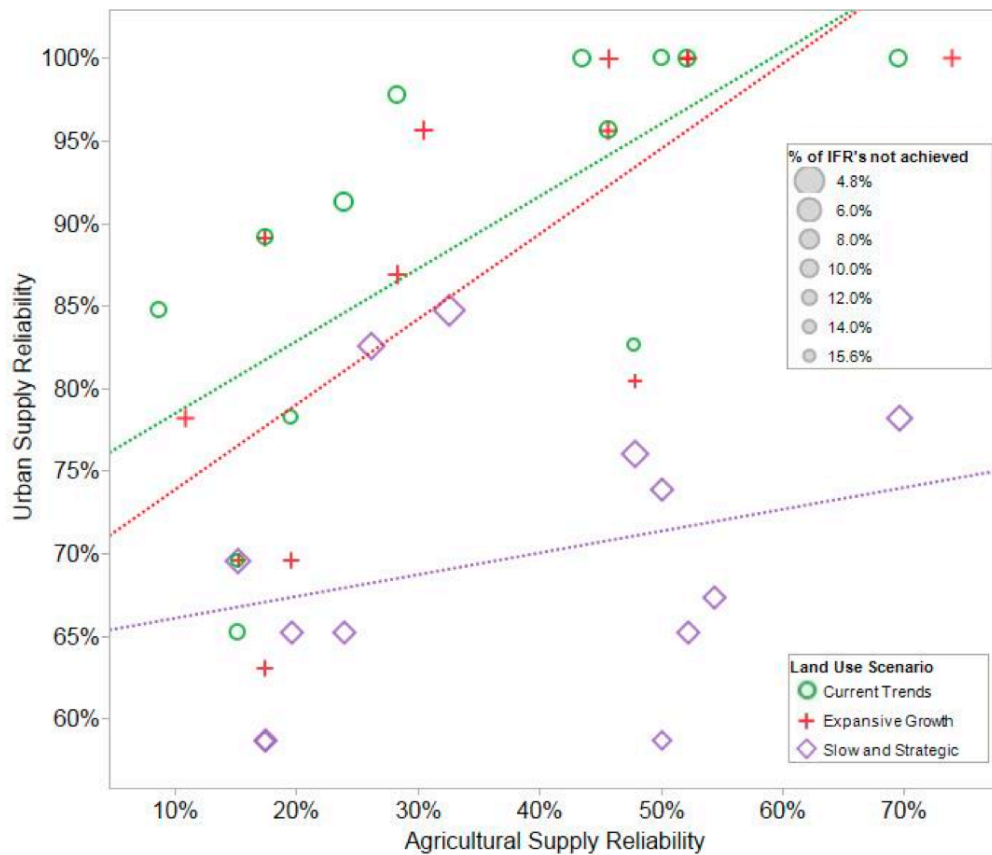
Figure 4.2. Distribution of Central Valley Urban Supply and Demand, by Decade



NOTE: Gray circles indicate individual scenario results. Horizontal solid lines indicate the median result across all scenarios. Shading indicates the 25th to 75th interquartile range. Dark Xs indicate results for the Current Trends land-use/Historical climate scenario.

Figure 4.3 shows a summary of outcomes over time for three of the four performance metrics from Table 3.3 in Chapter Three—urban supply reliability, agricultural supply reliability, and the frequency with which IFRs are not met. The range of performance varies widely across each of the three metrics. Agricultural supply reliability ranges between 5 percent and 75 percent; urban supply reliability ranges between 55 percent and 100 percent; percentage of unmet IFRs ranges between 5 and 15. Some scenarios show good performance across each of the three metrics, and some show very poor performance across all three metrics. There is a strong positive relationship between urban and agricultural supply reliability for the Current Trends (circles) and Expansive Growth (pluses) land-use scenarios. For the Slow and Strategic Growth land-use scenario, IFRs are prioritized more highly than urban and agricultural reliability, leading to fewer missed IFRs (bigger symbols) but at the expense of urban supply reliability.

Figure 4.3. Urban and Agricultural Supply Reliability Across Scenarios Under the Current Management Baseline



NOTE: Each symbol shows results for agricultural supply reliability (horizontal axis), urban supply reliability (vertical axis), and percentage of monthly IFRs not met (size of symbol). Smaller symbols and those toward the lower left corner indicate lower performance. Dashed lines show the linear relationships between urban and agricultural supply reliability for each of the three land-use scenarios.

What Are the Vulnerabilities of the Current Management Baseline?

We next establish definitions for what constitutes a vulnerability of the current management baseline—in other words, which outcomes would not meet California’s goals. For this proof-of-concept analysis, the research team, not stakeholders or decisionmakers, set these definitions. In the analysis for the final water plan, stakeholders and decisionmakers will define vulnerabilities. Using these definitions of vulnerability, we can summarize the overall vulnerability of the current management baseline. This assessment is used as a baseline for comparing the effects of management strategies and response packages.

Definition of Vulnerabilities

Thresholds defining acceptable performance for the performance metrics are as follows:

- agricultural supply reliability: In 50 percent or more of all years, 95 percent of demand is met.¹¹
- urban supply reliability: In 80 percent or more of all years, 99 percent of demand is met.
- frequency of not meeting IFRs: No more than 10 percent of monthly requirements across all IFRs are missed.

We defined a value function to distinguish futures in which a response package would meet its objectives across a sufficient number of metrics from futures in which it would not. Note that, much like the satisficing thresholds described earlier, such a value function should be defined in conjunction with decisionmakers and stakeholders. There are many complex ways to address multicriterion value functions. For simplicity, we chose the following value function, which is referred to as total vulnerability: failure to meet objectives under *two or more* metrics.

We experimented with other satisficing thresholds and definitions of total vulnerability. Although exact values for the vulnerability analysis differed depending on the definitions adopted, the general outcomes were similar. For the CWP Update 2013, these thresholds will be revisited and developed in consultation with CWP stakeholders.

Summary of Vulnerabilities

Table 4.1 summarizes the vulnerability of the current management baseline with respect to the three performance metrics and total vulnerability. The current management baseline is most vulnerable with respect to agricultural supply reliability (75 percent). As measured by the total vulnerability metric, the current management baseline is vulnerable in 15 of the 39 scenarios (38 percent).

Table 4.1. Percentage of Vulnerable Futures in the Current Management Baseline

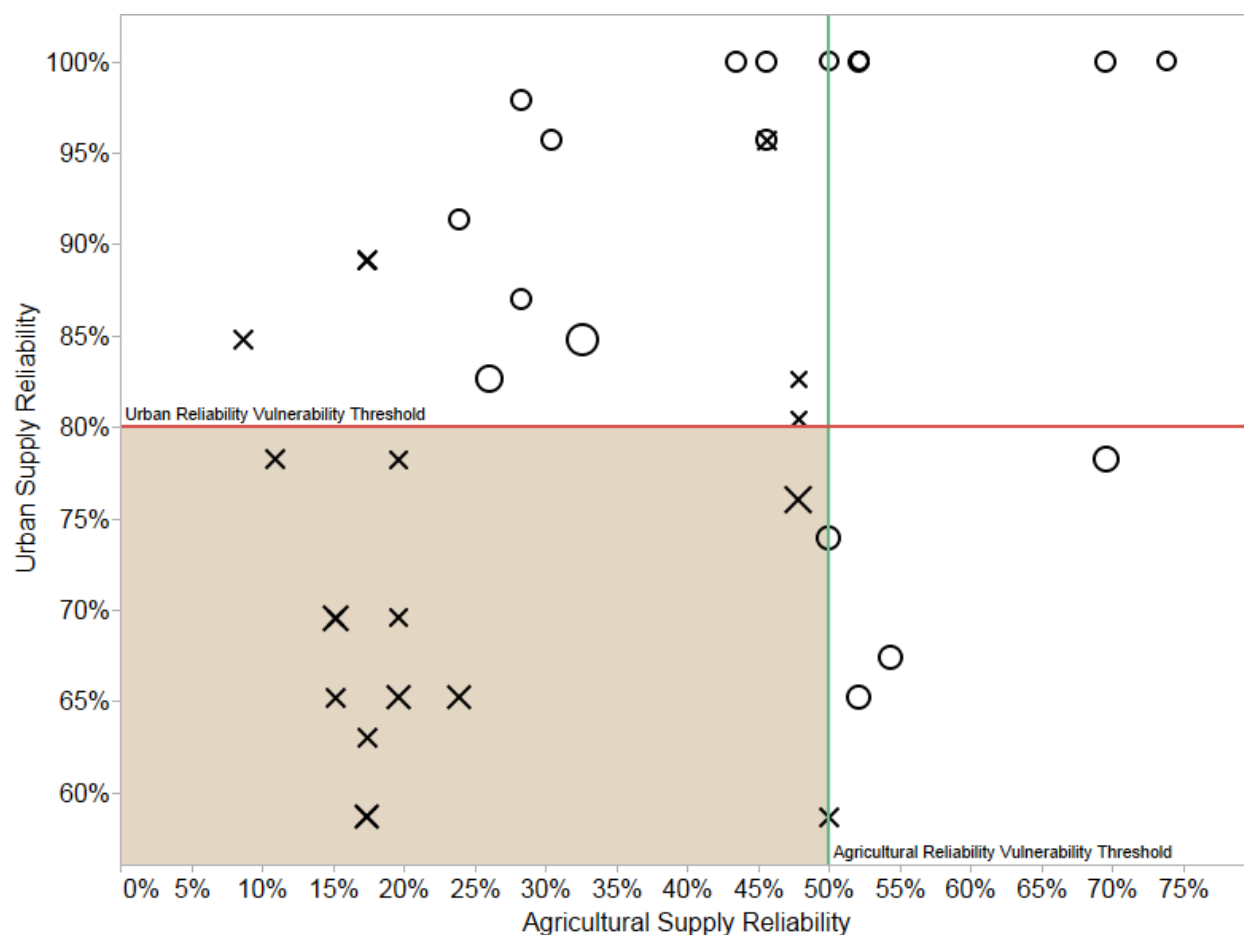
Performance Metric	Percentage of Vulnerable Futures
Agricultural supply reliability	75
Urban supply reliability	45
Missed environmental flow requirements	45
Total vulnerability (failure in two or more metrics)	38

Figure 4.4 shows the same results as Figure 4.3 but indicates the futures in which the current management strategy would be vulnerable (i.e., would not meet the thresholds for acceptable performance for two of the three metrics). All points that are to the left of the agricultural supply reliability threshold and below the urban supply reliability threshold (i.e., the shaded area) are

¹¹ DWR and the planning team received feedback on this analysis suggesting that the 50-percent threshold for agricultural demand was inappropriately low. These thresholds are being reconsidered for the CWP Update 2013.

vulnerable. Some points above the shaded region in the graph are also vulnerable because of poor performance with respect to the environmental flow metric and the agricultural supply reliability metric. This shows that, although many scenarios lead to acceptable results, there are many scenarios that are vulnerable in two or three of the key metrics.

Figure 4.4. Vulnerable Urban and Agricultural Supply Outcomes Across Scenarios Under the Current Management Baseline



NOTE: Each point represents one future under current management conditions. The Xs represent futures in which policy objectives are not met; circles represent futures in which policy objectives are met. The size of each symbol represents the number of IFRs missed, ranging between 4.8 percent and 15.6 percent. Smaller symbols represent higher percentages of unmet requirements.

Characteristics of Vulnerabilities

The results shown in Figure 4.4 clearly indicate that the current management approach is vulnerable to many of the plausible future conditions described by the scenarios. However, not all future conditions lead to poor performance. We next conducted a statistical analysis of the simulations to understand which external conditions lead to vulnerabilities. This information was

used in two ways: (1) to guide the development of response packages and (2) the specification of signposts—conditions to monitor over time that should trigger additional strategies.

To describe future vulnerable conditions, we first characterized the scenarios by primary driving factor. For example, for each demographic and land-use scenario, we calculated the following factors:

- population growth rate
- change in irrigated land area.

For each climate scenario, we calculated the following factors:

- average temperature
- temperature trend
- average annual precipitation
- temperature and precipitation in summer months
- temperature and precipitation in winter months
- temperature and precipitation from 2040 to 2050.

We next use the PRIM algorithm (see Chapter Two) to define a *decision-relevant* scenario that leads the current management strategy to perform poorly for the total vulnerability metric (Table 4.2). This composite scenario is defined solely by temperature trend and average annual precipitation. For these reasons, we call this composite scenario the Hot and Dry scenario. This composite scenario accounts for 75 percent of the vulnerable futures (a measure of *coverage*, as described in Chapter Two), and 100 percent of the futures making up this scenario are vulnerable (a measure of *density*).

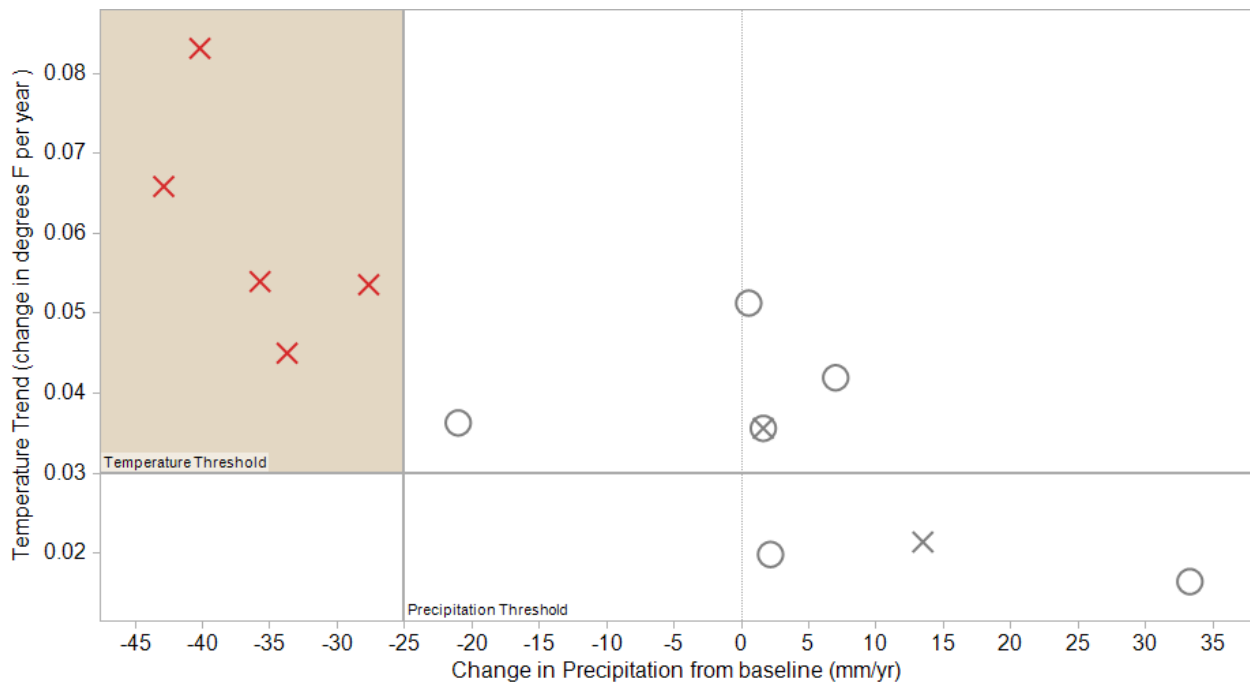
Table 4.2. Summary Table for the Hot and Dry Vulnerability Scenario Identified for the Total Vulnerability Metric

Decision-Relevant Scenario Name: Hot and Dry	
Metric: Total vulnerability	Composite Scenario Definition:
Vulnerable Cases: 20 of 39	<ul style="list-style-type: none"> • Change in precipitation from historical baseline < -25 mm/year • Temperature trend > 0.03 degrees/year
Decision-Relevant Scenario Statistics:	
<ul style="list-style-type: none"> • Density: 100% • Coverage: 75% 	

Figure 4.5 shows the results of the current management baseline strategy outcomes plotted with respect to the two key dimensions of the Hot and Dry composite scenario definition—the change in 2050 precipitation from baseline and the trend in temperature. As in Figure 4.4, Xs indicate those cases that are vulnerable, and circles indicate those cases that are not vulnerable. The red coloring indicates the cases that are described by the Hot and Dry composite scenario. Figure 4.5 shows that these two purposefully simple climate parameters—temperature trend and change in precipitation—do not explain all the vulnerable outcomes. Specifically, there are two climate sequences that lead to poor performance but do not fall within the Hot and Dry

composite scenario definition (the two gray Xs in Figure 4.5). These climate sequences exhibit other characteristics that lead to low system performance. For example, one of them includes a significant drought that is masked by above-average precipitation early in the simulation. This highlights the inherent trade-off between defining decision-relevant scenarios that are simple and interpretable versus defining those conditions that lead to all vulnerable outcomes.

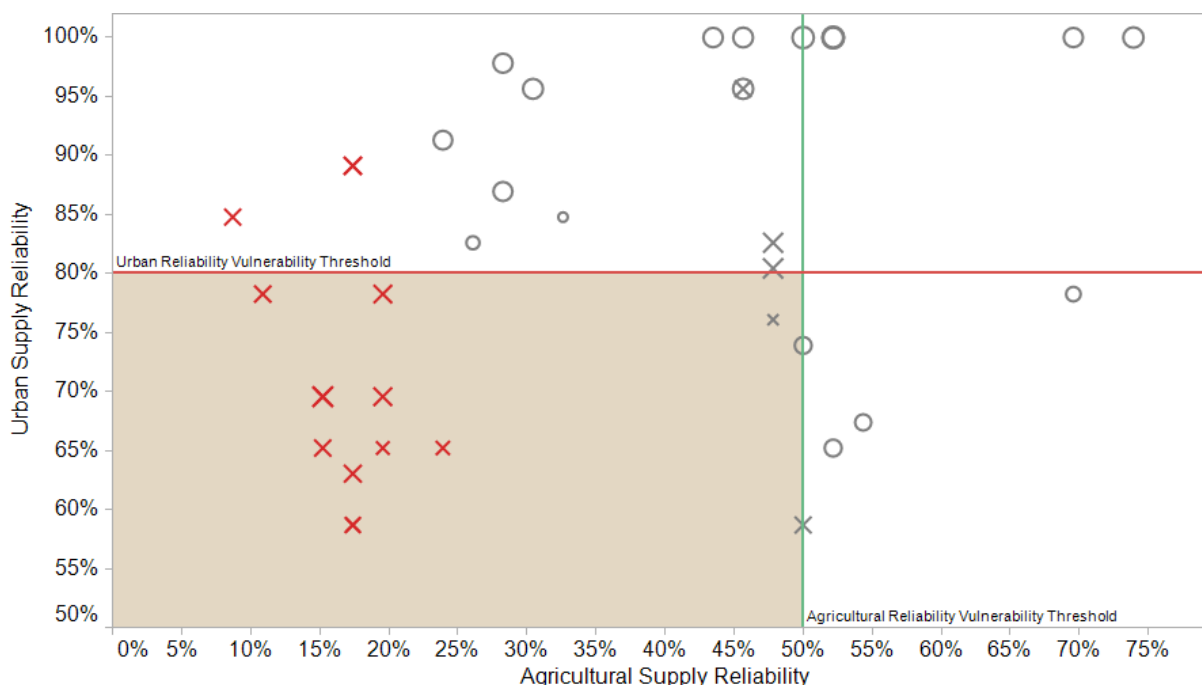
Figure 4.5. Climate Trends (temperature trends and changes in precipitation) for Each Future



NOTE: Each point represents one future under the current management baseline strategy. The Xs represent futures in which policy objectives are not met, and circles represent futures in which policy objectives are met. Red symbols represent outcomes that are described by the Hot and Dry composite scenario; gray symbols represent outcomes that are not described by the Hot and Dry composite scenario, i.e., not vulnerable. Note that the Hot and Dry composite scenario does not describe 25 percent of the vulnerable outcomes. Because there are only 12 unique climate sequences used to generate 36 futures, each combination of temperature trend and change in precipitation represents three results.

Figure 4.6 illustrates the coverage and density of the Hot and Dry composite scenario by showing the same results as in Figure 4.4 but by coloring red those results that are described by the Hot and Dry composite scenario. One can see that the Hot and Dry composite scenario encompasses the majority of vulnerable cases while not encompassing many nonvulnerable cases.

Figure 4.6. Vulnerable and Nonvulnerable Urban and Agricultural Supply Outcomes Described by the Hot and Dry Composite Scenario Across Futures Under the Current Management Baseline



NOTE: Each point represents one future for the current management baseline. The Xs represent futures in which policy objectives are not met, and circles represent futures in which policy objectives are met. The size of each symbol represents the number of IFRs missed, ranging between 4.8 percent and 15.6 percent. Larger symbols represent higher percentages of unmet requirements. Red symbols represent outcomes that are described by the Hot and Dry composite scenario; gray symbols represent outcomes that are not.

The scenario-discovery results suggest that the current management baseline is highly vulnerable to future climate conditions, conditions in accordance with estimates from global climate models. Even slight decreases in average annual precipitation and relatively modest increases in temperatures lead to outcomes that fail to meet objectives. Although other outcomes do vary across the demographic and land-use scenarios, the differences are dominated by changes due to the climate.

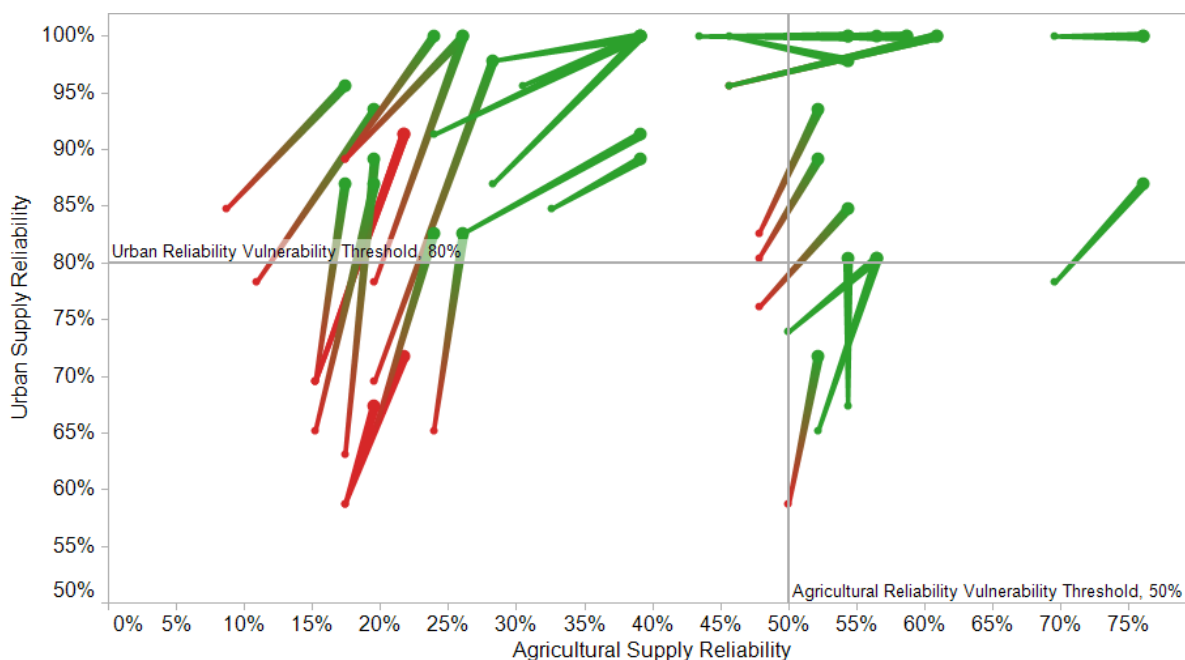
Chapter Five. Results: Mitigating Vulnerabilities Through Response Packages

Chapter Four analyzed how well the current management baseline approach would perform across a wide range of futures with respect to three reliability metrics and a summary metric. We found that hot and dry climate sequences were the primary future conditions under which the region is vulnerable. This chapter analyzes supply augmentation options and describes their potential for reducing vulnerabilities. It then describes the key trade-offs among the augmentation options in terms of reducing vulnerabilities and cost. It ends with a discussion of how the results could help decisionmakers select a response package based on expectations of facing the hot and dry conditions defined in Chapter Four and tolerance for accepting unfavorable outcomes.

How Would Additional Management Strategies Reduce Vulnerabilities of the Current Management Baseline?

We next evaluated how the implementation of different response packages (Table 3.5 in Chapter Three) would improve outcomes and reduce vulnerabilities. Figure 5.1 shows, as an example, how the Increased Efficiency response package improves urban and agricultural supply reliability results across the futures evaluated for Chapter Four and, in some cases, converts the outcomes from vulnerable (red dots) to nonvulnerable (green dots). In a more comprehensive analysis with more futures defining uncertainty, one could use the scenario-discovery analysis from Chapter Four to focus the evaluation of strategies on those futures in which the baseline strategy is found to be vulnerable.

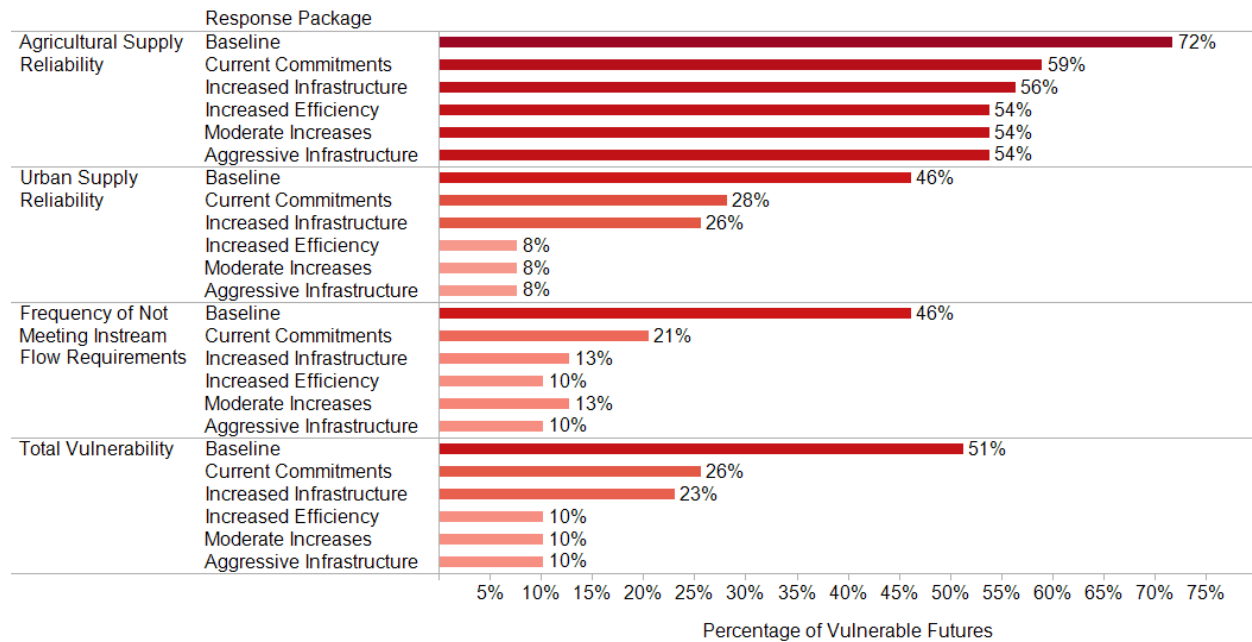
Figure 5.1. Comparison of Outcomes for the Current Management Baseline and the Increased Efficiency Response Package



NOTE: Each object represents an outcome under the current management baseline (thin end) and Increased Efficiency response package (thick end) for a single future. Red represents outcomes that are vulnerable, and green represents outcomes that are not vulnerable.

Figure 5.2 summarizes the effect that each of the response packages has on the three performance metrics and the total reliability metric. For agricultural supply reliability, the percentage of vulnerable futures declines from 72 to around 55 for three of the five response packages—those in which agricultural efficiency improves to the greatest extent. Urban supply reliability also improves the most for the three response packages in which agricultural efficiency improves the most—declining to less than 10 percent of the futures examined. All response packages have positive effects on the metric measuring frequency of not meeting IFRs. For the total vulnerability metric, the best outcomes are achieved for the Increased Efficiency, Moderate Increases, and Aggressive Infrastructure response packages: Each reduces the percentage of vulnerable futures from 51 to about 10.

Figure 5.2. Percentage of Vulnerable Futures for the Current Management Baseline and Five Response Packages, by the Four Reliability Metrics



NOTE: Darker red bars indicate higher percentages of vulnerable futures.

How Resilient Would Response Packages Be to Future Climate Change?

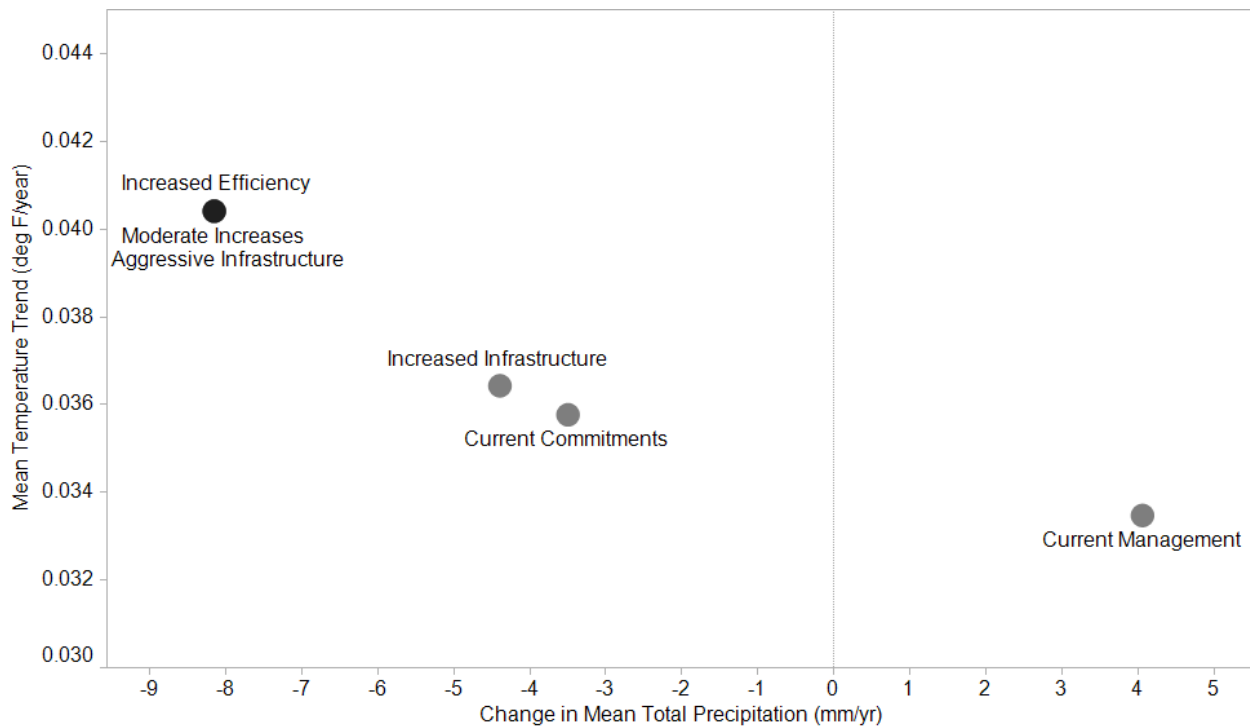
If the region were to implement one of the evaluated response packages, the system would become more resilient to the conditions described by the Hot and Dry composite scenario. Table 5.1 summarizes the changes in percentages of futures that lead to vulnerable conditions, defined by the total vulnerability metric, both within and outside the Hot and Dry composite scenario.

Table 5.1. Percentage of Futures Leading to Vulnerabilities Inside and Outside the Hot and Dry Vulnerability Scenario

Baseline or Response Package	Percentage of Futures Leading to Vulnerabilities	
	Within the Hot and Dry Composite Scenario	Outside the Hot and Dry Composite Scenario
Current management baseline	100	26
Current Commitments	60	4
Increased Infrastructure	53	4
Increased Efficiency	27	0
Moderate Increases	27	0
Aggressive Infrastructure	27	0

The implementation of response packages will also change the nature of conditions to which the system is resilient. Figure 5.3 illustrates this effect by showing the average temperature trend and change in precipitation (assuming equal weights for all scenarios) for the nonvulnerable conditions for each response package. The results here suggest that the current management baseline, for example, would generally be resilient only to future climate conditions in which precipitation increases. The Current Commitments response package, however, would increase the resilience of the system by performing adequately in conditions that are, on average, drier. The implementation of the Increased Efficiency, Moderate Increases, or Aggressive Infrastructure response package would increase the resilience of the system even more, to conditions in which precipitation declines by almost 8 mm per year and temperatures increase by about 0.04 degree Fahrenheit per decade on average. Because of the relative sparseness of the climate scenarios evaluated, however, there are no actual simulations that correspond the average climate conditions shown in Figure 5.3. It is also important to note that these results depend strongly on the scenarios included in the experimental design (Table 3.5 in Chapter Three). A broader sampling of climate conditions could lead to different climate resilience results.

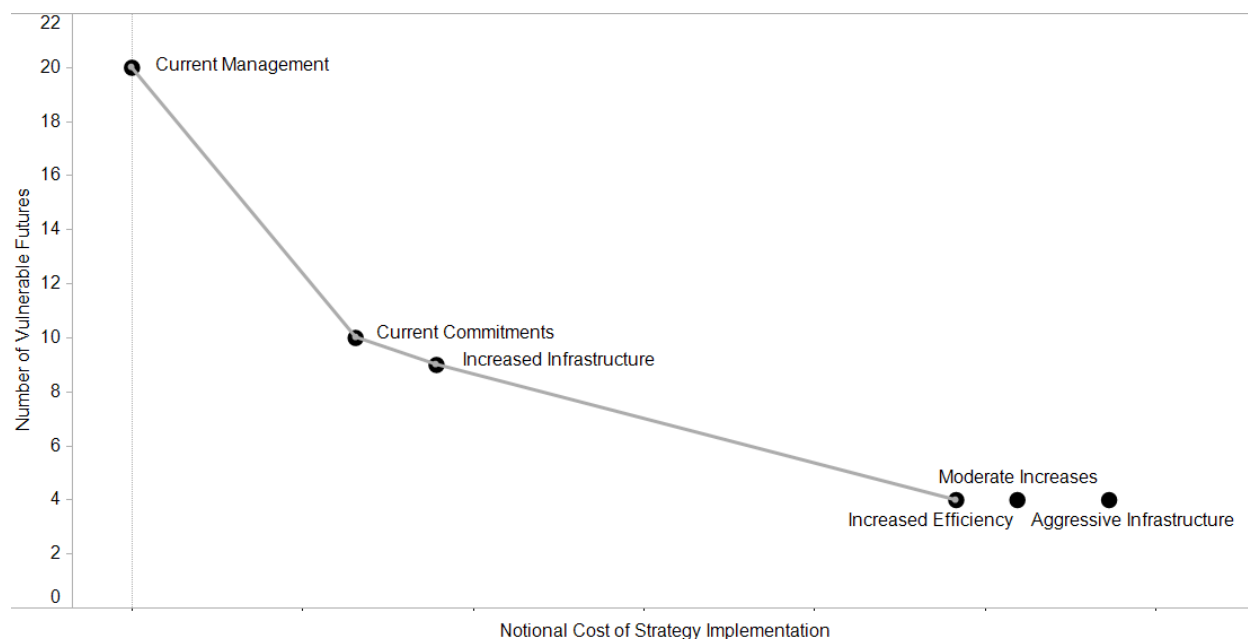
Figure 5.3. Average Temperature Trend and Change in Precipitation of Futures in Which the Response Package Would Meet Objectives



What Are Key Trade-Offs Among Response Packages?

If level of effort (and other effects of the augmentation strategies not captured by this analysis) were not a consideration, the Increased Efficiency, Moderate Increases, and Aggressive Infrastructure response packages would clearly be the equally preferred options. When costs of the management strategies are factored in, a trade-off emerges. Figure 5.4 plots each response package by the percentage of futures that are vulnerable for the metrics for total vulnerability (vertical axis) and the notional cost of strategy implementation (horizontal axis). In general, the more-effective response packages cost more. However, additional efforts beyond the Increased Efficiency response package do not further reduce vulnerabilities. Thus, Increased Efficiency is always preferable to Moderate Increases or Aggressive Infrastructure. The line on the graph traces out a simple trade-off curve that one could consider when choosing among strategies. Note that a more involved RDM analysis would consider the cost uncertainty along with the other uncertainties when defining vulnerabilities.

Figure 5.4. Trade-Off Curve of Notional Cost of Strategy Implementation and Number of Vulnerable Futures



The three costliest response packages—Increased Efficiency, Moderate Increases, and Aggressive Infrastructure—are all equally effective at reducing the number of vulnerable futures. These response packages have identical levels of efficiency with which water would be used, suggesting that improving efficiency has a much larger effect than other water-management strategies (i.e., recycling and conjunctive water use). Note that these results reflect assumptions made for this proof-of-concept analysis that will be refined for the CWP Update 2013.

How Does This Analysis Inform Decisionmaking?

The trade-off graph between the number of vulnerable futures and costs provides a first look at how decisionmakers in the region might compare different management strategies. Figure 5.4, for example, suggests that the most cost-effective way to reduce the vulnerabilities identified in this proof-of-concept analysis would be through the implementation of the Increased Efficiency response package.

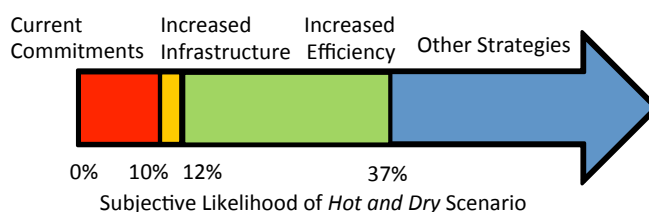
There are several reasons that such a choice may not be straightforward. First, this decision assumes that the value of reducing these vulnerabilities exceeds the costs of implementing this strategy. To quantify the value of reducing these vulnerabilities, one requires a function to assign values to each outcome for all plausible scenarios. This proof-of-concept analysis did not attempt to quantify these costs.

One also must estimate the relative likelihood of each future and assume that the futures evaluated fully represent the plausible range of outcomes. RDM helps address these requirements by defining composite scenarios that matter with respect to decisions under

evaluation. Specifically, this proof-of-concept analysis defined a composite scenario that concisely defines conditions in which the current management baseline approach would perform poorly—the Hot and Dry composite scenario. To the extent that this composite scenario captures all unacceptable performance, it represents the only scenarios that matter. One can then weight the outcomes for the decision-relevant scenario and all other outcomes to derive an expected outcome, contingent upon a subjective expectation of the probability for the decision-relevant scenario. The outcome of such an analysis is the identification of the response package that leads to the highest expected value outcomes (or lowest cost outcomes) across a range of different subjective likelihoods for the decision-relevant scenario.

For this proof-of-concept analysis, we could not estimate the cost of each future; instead, we calculated which response package would lead to a nonvulnerable outcome at least 90 percent of the time for different subjective likelihoods of the Hot and Dry composite scenario. Figure 5.5 shows that, if someone’s subjective likelihood of facing the Hot and Dry composite scenario were less than 10 percent, then the Current Commitments response package would be the most cost-effective. If the likelihood were between 12 and 37 percent, however, the Increased Efficiency response package would be the most cost-effective. Lastly, if likelihoods were greater than 37 percent, then other strategies not evaluated in this analysis would be needed to meet the 90-percent reliability goal.

Figure 5.5. Recommended Response Package for a Range of Subjective Likelihoods of the Hot and Dry Composite Scenario



NOTE: Lowest-cost response packages that lead to a 90-percent likelihood of facing a nonvulnerable outcome, contingent on the range of subjective likelihoods of the Hot and Dry composite scenario, and an equal weighting of all scenarios within and outside the Hot and Dry composite scenario. For example, the Increased Efficiency response package is recommended if the subjective likelihood of the Hot and Dry scenario is between 12 and 37 percent.

The proof-of-concept analysis does not include additional iterations through the RDM process (Figure 2.1 in Chapter Two). A more complete analysis might evaluate the remaining vulnerabilities of a selected robust response package—for example, Increased Efficiency. This information could then be used to inform the development of a more adaptive version of the response package. Lempert and Groves (2010) provides an example of how adaptive strategies can increase the robustness of long-term water-management plans.

Chapter Six. Discussion

This proof-of-concept analysis has demonstrated how RDM might be applied to the CWP analysis of vulnerabilities and response packages. It shows how the WEAP Central Valley Model could be used to generate different scenarios of future conditions and how these results could be used to define those conditions that would lead to poor performance in the current management baseline. Next, we show how the implementation of response packages could reduce vulnerabilities and lead to a more resilient system. Lastly, we show one example of how the trade-off between reductions in vulnerabilities and cost for the different response packages can be used to inform long-term planning for the Central Valley.

Because of a desire to focus on methodology, the proof-of-concept analysis was not designed to provide policy recommendations, nor have we demonstrated all aspects of RDM. For example, we did not develop and evaluate response packages that evolve over time, a feature likely to be very important for the successful long-term management of the Central Valley. This proof-of-concept analysis also focused on just a few key performance metrics; we based the vulnerability and trade-off analysis on a single aggregate metric. It used only notional estimates of costs for the response packages and did not consider the value of outcomes beyond the reductions in vulnerabilities. It also did not demonstrate how iteration through the RDM steps could help identify increasingly robust response packages.

Its treatment of future climate uncertainty was notably limited by the use of 12 downscaled global climate model simulations. These climate scenarios likely underrepresent climate variability. A recent study, for example, evaluated a single climate model many times using the same atmospheric and ocean forcing but with slight perturbations of initial conditions (Deser et al., 2012). The simulations show a wide range of future temperature and precipitation conditions over the extratropical regions, such as California. These results suggest that the predictability of future climate is limited because of natural variability, and a thorough robustness analysis would likely require a more expansive set of climate scenarios than evaluated for this proof-of-concept study.

RDM, however, is well suited to address these challenges through iteration. The CWP Update 2013, for example, will develop an expanded set of climate scenarios to provide a more comprehensive set of climate conditions to use for testing the robustness of different response packages.

The analysis for the CWP Update 2013 will address some but not all of these issues. Specifically, it will evaluate a larger set of scenarios to span a wider range of plausible future conditions, including climate. The WEAP model will report on a larger set of performance metrics, and the vulnerability analysis will define vulnerable conditions for each of these performance metrics. The final trade-off analysis will compare outcomes not just by reductions

in total vulnerability and cost but also by reductions in vulnerability for the different performance metrics. Lastly, the final trade-off analysis will be based on improved estimates of implementation costs.

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